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(71) Applicant *(for all designated States except US)*: GAMBRO LUNDIA AB [SE/SE]; Magistratsvägen 16, P.O. Box 10101, S-220 10 Lund (SE).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: STERNBY, Jan, Peter [SE/SE]; Sparsnogatan 45, S-226 52 Lund (SE).

(74) Agents: WIHLSSON, Joakim et al.; Bjerkéns Patentbyrå KB, Östermalmsg. 58, S-114 50 Stockholm (SE).

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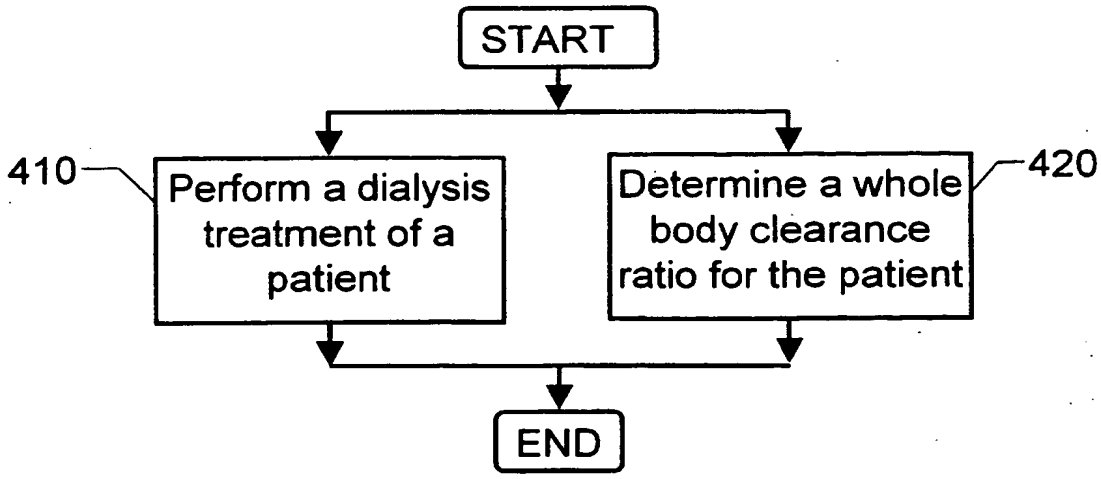
(54) Title: A METHOD AND AN APPARATUS FOR DETERMINING THE EFFICIENCY OF DIALYSIS



(57) Abstract: The invention relates to characterization of a dialyzer's capacity to accomplish a dialysis clearance of a patient, and strategies for improving the efficiency of a dialysis treatment of the patient. The invention involves determining a whole body clearance ratio (420) for a dialysis treatment of a patient (410). The whole body clearance ratio expresses how well the patient responds to a potential cleaning capacity of a dialyzer, which is used to perform the treatment.

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Dialysis Clearance

THE BACKGROUND OF THE INVENTION AND PRIOR ART

The present invention relates generally to dialysis clearance. More particularly the invention relates to a method of estimating a process efficiency of a dialysis system according to the preamble of claim 1, a method of estimating a whole body clearance ratio according to the preamble of claim 6, corresponding computer programs and computer readable media according to claims 11 and 13 respective 12 and 14, an apparatus adapted to estimate a whole body clearance ratio according to claim 16, as well as use of this apparatus according to claim 17. The invention also relates to a method of performing a dialysis treatment program according to the preamble of claim 15.

Generally in dialysis, there is a large need to better understand the differences between patients, and what factors determine the achievable efficiency of the dialysis treatment in the individual patients. In theory, a number of different parameters may be used to characterize a dialyzer's capacity to filter waste products from a patient's bloodstream and restore the normal constituents of his/her blood. For example, models for solute concentrations in the different body parts may be used. It is also possible to characterize patients by measurable parameters, which in turn, may be used to improve the efficiency of the dialysis treatments.

A good model to use in order to understand the process of dialysis for cleaning the body from a solute is the so-called regional blood flow model for the solute distribution in the body, which was developed by Daugirdas and Schneditz. Urea is a common marker molecule for the description of the dialysis progress, and will be used for the following discussion for this purpose. However, the same discussion may also be applied to

other solutes, such as creatinine, glucose, phosphate and other ions. According to one model, the human body includes two urea containing pools; one large pool of volume V_L, which is perfused by a relatively small blood flow Q_L, and one small pool of volume V_H, which is perfused by a relatively large blood flow Q_H, see figure 1. The small pool of volume V_H represents the blood in the internal organs, such as the liver etc., and the large pool of volume V_L represents blood located in the muscles, the skin and the like. Due to the comparatively large blood flow Q_H to the small pool of volume V_H, this pool will be much more efficiently depurated than the large pool of volume V_L. Thus, after an initial transient, the concentration of urea C_H in the small pool of volume V_H will be lower than the concentration of urea C_L in the large pool of volume V_L. Before returning to the heart η, the blood from the two pools V_L and V_H will be mixed, and a mixed venous urea concentration C_{mv} therefore becomes a weighted mean value of the two pool concentrations C_L and C_H, with the respective flow weights Q_L and Q_H, according to the following:

$$C_{mv} = \frac{Q_L \cdot C_L + Q_H \cdot C_H}{Q_L + Q_H}$$

The denominator here represents the total blood flow $Q_L + Q_H$. Note that the mean value C_{mv} falls between the two pool concentrations C_L and C_H. However it will be closer to the concentration of urea C_H in the small pool of volume V_H because its weight Q_H is larger than Q_L. Before reaching the heart η, the mixed venous blood will also mix with partly cleaned blood from the dialyzer 130, so that the concentration of urea in the heart η which is equal to a concentration C_b returning to the access and the dialyzer, will be lower than all other concentrations.

When discussing the depuration of the whole body it is of interest to also discuss the mean concentration of urea in the whole body. This is sometimes referred to as the equilibrated concentration C_{eq}, since it is the concentration which would be the result if the body were left to equilibrate the pool concent-

rations C_L and C_H. In our regional blood flow model, the equilibrated concentration C_{eq} is:

$$C_{eq} = \frac{V_L \cdot C_L + V_H \cdot C_H}{V_L + V_H}$$

The equilibrated concentration C_{eq} will also fall between the pool concentrations C_L and C_H. However, it will be closer to the concentration of urea C_L in the large pool of volume V_L because of the volume V_L being larger than the volume V_H. Consequently, we obtain the relationship:

$$C_L > C_{eq} > C_{mv} > C_H > C_b$$

Clearance is an entity which is used to describe the efficiency of the depuration process. More precisely, clearance is defined as the removal rate divided by the concentration of the substance in the fluid to be cleaned. Normally, a dialyzer clearance K, which is used to characterize dialyzers at different flow conditions, is defined as the removal rate divided by the concentration C_b, i.e. the concentration in the blood returning from the heart-lung system to the access and the dialyzer. A part of the cleaned blood from the dialyzer which is mixed with the blood returning from the body goes from the heart and enters directly into the dialyzer again. This is called cardiopulmonary recirculation, and is the reason why blood entering the dialyzer has a lower concentration (i.e. C_b) than the blood returning from the body. A so-called effective clearance K_{eff} is instead defined as the removal rate divided by the mixed venous concentration C_{mv}, and is a better measure of the effective depuration of the patient. The effective clearance K_{eff} can be estimated if the removal rate is measured either on the blood side or on the dialysate side of the dialyzer, and the mixed venous concentration (or the systemic blood concentration) C_{mv} is measured by stopping the blood pump during an interval (say 1 minute) to let the effect of the cardiopulmonary recirculation disappear before a blood sample is drawn. Another simple

method to estimate the effective clearance is to measure the effect in the outlet dialysate conductivity of a step in the inlet dialysate conductivity, for instance according to the procedures proposed in the documents EP 547 025, EP 658 352 and US 6,217,539.

However, a still better measure would be to describe the cleaning of the whole body equilibrated concentration C_{eq}. This so-called whole body clearance K_{wb} (or K_{eq}) is defined as the removal rate divided by the equilibrated concentration C_{eq}. Moreover, due to the relationships between the corresponding urea concentrations, we obtain the following relationships between the clearances:

$$K > K_{eff} > K_{eq}$$

Since it is relatively difficult to measure the pool concentrations C_L and C_H there is no straightforward way to measure the equilibrated concentration C_{eq}, and consequently, the whole body clearance K_{wb} is also difficult to estimate. One possibility to measure the equilibrated concentration C_{eq} is to wait until the concentrations have equilibrated after the treatment. However, this takes relatively long time (half an hour up to one hour) and is therefore impractical.

The interest in the whole body clearance K_{wb} originates from the fact that this measure describes the cleaning effect of the dialyzer on the body, whereas the dialyzer clearance K and the effective clearance K_{eff} constitute descriptions of the cleaning capacity of the dialyzer and the dialyzer together with the heart-lung system η and λ respectively. The dialyzer clearance K is known from the dialyzers data sheet, and the relationship between this measure and the effective clearance K_{eff} is given by the expression:

$$K_{eff} = \frac{K}{1 + K/Q}$$

where Q is the total systemic blood flow, i.e. $Q = Q_L + Q_H$. Unfortunately, the relationship between the effective clearance K_{eff} and the whole body clearance K_{wb} is much less trivial.

It is nevertheless possible to study the theoretical relationship between the pool concentrations C_L and C_H. Setting up a mass balance equation for each of the two pools of volume V_L and V_H leads to a system of two coupled first order differential equations for the concentrations C_L and C_H. If we include the effect of a constant ultrafiltration rate, the pool volumes V_L and V_H will decrease linearly over time, and the differential equations for the concentrations C_L and C_H will have variable coefficients.

Daugirdas and Schneditz have managed to solve these equations for the case when the urea generation in the pool volumes V_L and V_H was included. Daugirdas and Schneditz studied the impact on the rebound of urea after treatment, i.e. the magnitude of the equilibration of urea concentrations after the treatment. However, the volumes V_L and V_H were allowed to *vary*, which in turn, led to a *non-steady state relationship* between the pool concentrations C_L and C_H. Thus, a reliable estimate of the whole body clearance K_{wb} could not be obtained.

The U.S. patent No. 6,258,027 discloses a method and a device for calculating dialysis efficiency with respect to a mass exchange of a solute in a fluid. However, no measure is determined which reflects the whole body clearance of the dialyzer on a patient.

SUMMARY OF THE INVENTION

The object of the present invention is therefore to alleviate the problems above and thus accomplish an improved estimation of the whole body clearance of the dialyzer on a particular patient and enabling identification of cases where an improvement is necessary, and probably possible.

According to one aspect of the invention, the object is achieved by the initially described method of estimating a process efficiency, wherein a whole body clearance ratio is determined, which expresses how well the patient responds to the potential cleaning capacity of a dialyzer.

An important advantage attained by this strategy is that the whole body clearance ratio provides an adequate measure of the actual usefulness of the dialysis treatment. Since each patient has his/her own characteristic response to a particular treatment, it is otherwise very difficult to determine the specific benefit of the dialysis process.

According to a preferred embodiment of this aspect of the invention, the whole body clearance ratio is determined by: measuring a final blood urea concentration, either immediately, or approximately one minute after the end of the treatment; measuring an equilibrated blood urea concentration no earlier than approximately one half hour to one hour after the end of the treatment; and dividing said final blood urea concentration by said equilibrated blood urea concentration. Thereby, a reliable measure is found, which reflects the process efficiency with respect to the patient.

According to another preferred embodiment of this aspect of the invention, the whole body clearance ratio is determined by: measuring an initial urea concentration; measuring, during the treatment at occasions being well spaced in time at least two subsequent urea concentration values after the treatment has started, a first value of said at least two values being measured no earlier than approximately one half hour after the treatment has started; deriving a starting urea concentration based on an extrapolation in time of said at least two values back to the start of the treatment; and dividing said starting urea concentration by said initial urea concentration.

According to yet another aspect of the invention, the object is

achieved by the initially mentioned method of estimating the whole body clearance ratio of a dialysis treatment of a patient, wherein the whole body clearance ratio is determined on the basis of a measurement of a slope of a logarithmic removal rate function, which describes how a urea concentration is lowered in course of the treatment. This slope is namely a key factor in the whole body clearance ratio.

According to a first preferred alternative under this embodiment of the invention, the method involves the steps of: determining an initial dialysate urea concentration; determining a total flow rate value representing the spent dialysate during the treatment, including any ultrafiltration; calculating, based on measurements performed during a steady state phase of the treatment, the slope of the logarithmic removal rate function; measuring a predialysis urea mass in the patient; and determining the whole body clearance ratio as the product of the slope and the predialysis urea mass, divided by the flow rate value and divided by the initial dialysate urea concentration.

According to a second preferred alternative under this embodiment of the invention, the method involves the steps of: calculating, based on measurements performed during a steady state phase of the treatment, the slope of said logarithmic removal rate function; determining an entire distribution volume; and determining the whole body clearance ratio as the product of said slope and said entire distribution volume divided by the potential cleaning capacity.

According to preferred embodiments of this aspect of the invention, the measurements relating to the slope of the logarithmic removal rate function may be performed either on a dialysate side or on a blood side of a dialysis system including the dialyzer and the patient.

According to a further aspect of the invention, the object is achieved by a computer program, which is directly loadable into

the internal memory of a computer, and includes software for controlling the above proposed method when said program is run on a computer.

According to another aspect of the invention the object is achieved by a computer readable medium, having a program recorded thereon, where the program is to control a computer to perform the above-proposed method.

According to yet another aspect of the invention, the object is achieved by an apparatus, which is adapted to estimate the whole body clearance ratio of a dialysis treatment of a patient. Again, by efficiency is meant how well the patient responds to a cleaning capacity of a dialyzer, which performs the treatment. The apparatus includes a urea monitor and a processor. The urea monitor circuit is adapted to: determine an initial dialysate urea concentration; determine a total flow rate of spent dialysate during the treatment (including any ultrafiltration); during a steady state phase of the treatment, measure a slope of a logarithmic removal rate function, which describes how a dialysate urea concentration is lowered in course of the treatment; and measure a predialysis urea mass in the patient. The processor is adapted to determine the whole body clearance ratio of the patient by multiplying the slope of the logarithmic removal rate function with the predialysis urea mass and dividing the result thereof by the flow rate and the initial dialysate urea concentration. In similarity with the above-proposed method, this apparatus is advantageous because it provides a measure of the actual usefulness of the dialysis treatment.

According to yet another aspect of the invention, the object is achieved by using the above the apparatus for estimating the whole body clearance ratio of a dialysis treatment of a patient according to the proposed method.

A general advantage attained by the invention is that, based on the whole body clearance ratio for a dialysis treatment of a

particular patient, a following treatment of the same patient can be made more efficient. Namely, if a relatively low ratio is determined, the next time, certain actions can be taken to improve the result of the dialysis. For instance, the treatment time can be prolonged, the composition of the dialysate can be altered, or some kind of intervention procedure with respect to the patient may be performed. The intervention procedure may involve subjecting the patient to physical exercise, massage, a change in the ambient temperature, an increased fluid intake, acupuncture, and/or medication affecting the systemic blood flow or the blood flow distribution in the patient's body.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is now to be explained more closely by means of preferred embodiments, which are disclosed as examples, and with reference to the attached drawings.

Figure 1 shows a schematic model of a patient's bloodstream, which is connected to a dialyzer according to the invention,

Figure 2 illustrates a patient being attached to an apparatus for estimating a whole body clearance ratio of a dialysis treatment according to an embodiment of the invention,

Figure 3 is a graph over a removal rate function describing a first example of how a urea concentration is lowered during a dialysis treatment,

Figure 4 shows a flow diagram which illustrates the general method of estimating a process efficiency of a dialysis system according to the invention,

Figure 5 shows a flow diagram which illustrates the general method of estimating a whole body clearance ratio of a dialysis treatment of a patient according to the

invention, and

Figure 6 a graph over a removal rate function describing a second example of how a urea concentration is lowered during a dialysis treatment, and

Figures 7-24 illustrate dialysis examples which further elucidate the strategy according to the invention.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Returning now to the figure 1, in contrast to Daugirdas and Schneditz, the invention presumes that the pool volumes V_L and V_H are constant. Thus, no ultrafiltration is presumed to take place, and the generation of urea is neglected. This means that it is possible to set up one differential equation for the ratio between the two pool concentrations C_L and C_H. Moreover, it can be shown that the ratio between the two pool concentrations C_L and C_H tends towards a constant. This in turn, means that the clearance ratio: "whole body clearance"-to-"effective clearance" K_{wb}/K_{eff} (which equals the ratio: "mixed venous concentration"-to-"equilibrated concentration" C_{mv}/C_{eq}) also tends towards a constant. The factors which determine the steady state ratios are the fraction of the large pool volume V_L to the entire blood volume $V = V_L + V_H$, the fraction of the blood flow Q_L in the large pool to the total systemic blood flow Q, and the fraction of the effective clearance K_{eff} to the total systemic blood flow Q. Consequently, besides the effective clearance K_{eff}, the clearance ratio is only determined by patient specific parameters. All of the above is true if we relate the whole body clearance K_{wb} to the dialyzer clearance K, instead of to the effective clearance K_{eff}. Normally, (for typical values) it takes approximately half an hour to one hour for a steady state level to be reached for these patient related parameters.

However, according to the invention, the ratio K_{wb}/K_{eff} or K_{wb}/K

is used to characterize a dialyzer's capacity with respect to different patients. Provided that this is done at a specific K or K_{eff} value, all the remaining parameters determining these ratios are patient specific, and may hence be used to specify how well the patient responds to the cleaning capacity of the dialyzer.

Figure 2 illustrates a situation where a patient 120 is connected to an apparatus 210 according to an embodiment of the invention. The apparatus 210 is adapted to estimate the efficiency (with respect to the whole body clearance ratio K_{wb}/K_{eff}) of a dialysis treatment of the patient 120 performed by a dialyzer 130.

The apparatus 210 includes a urea monitor circuit 211 and a processor 212. The urea monitor circuit 211 is adapted to measure a predialysis urea mass m_0 in the patient 120. The urea monitor circuit 211 is also adapted to determine an initial dialysate urea concentration C_{d0} (e.g. by means of samples taken between t_1 and t_2 in figure 3, and an extrapolation back to zero) and a total flow rate Q_d of spent dialysate during the treatment (including any ultrafiltration). During steady state phase of the treatment, the urea monitor circuit 211 measures a slope K_{wb}/V of a logarithmic removal rate function, which describes how a dialysate urea concentration is lowered in course of the treatment (e.g. by means of samples taken between t_3 and t_4 in figure 3).

The processor 212 is adapted to determine the whole body clearance ratio K_{wb}/K_{eff} for the patient 120 on the basis of the predialysis urea mass m_0, the slope K_{wb}/V of the logarithmic removal rate function, the initial dialysate urea concentration C_{d0} and the total flow rate Q_d. Specifically, the processor 212 calculates the whole body clearance ratio K_{wb}/K_{eff} according to the expression:

$$\frac{K_{wb}}{K_{eff}} = \frac{K_{wb}}{V} \cdot \frac{m_0}{Q_d \cdot C_{d0}}$$

I.e. the whole body clearance ratio K_{wb}/K_{eff} is determined as the

product of the slope K_{wb}/V and the predialysis urea mass m_0, divided by the flow rate Q_d and the initial dialysate urea concentration C_{d0}.

The rationale behind this is that it is possible to calculate K_{wb}/V as the slope of a logarithm curve, which describes the urea concentration in the spent dialysate. The urea concentration may be measured continuously by the urea monitor 211. These measurements also render it possible to determine the predialysis urea mass m_0, for example according to the procedure proposed in US 6,258,027.

By definition, the predialysis urea mass m_0 equals the product of the distribution volume (i.e. the entire body water volume V in case of urea) and the plasma water concentration C_{pw}, i.e. $m_0 = V \cdot C_{pw}$. The plasma water concentration C_{pw} may be measured in a blood sample drawn from the patient 120 before the treatment starts, and since the volume V is the volume of water (with dissolved ions), the measured plasma concentration must be the plasma water concentration C_{pw}. An effective plasma water clearance, on the other hand, can be calculated from the removal rate and the plasma water concentration C_{pw}. This can be done at the start of the treatment.

However, the blood sample drawn from the patient before the treatment starts reflects an equilibrated (i.e. systemic) urea concentration. An effective clearance K_{eff} may therefore be calculated according to the expression:

$$K_{eff} = \frac{Q_d \cdot C_{d0}}{C_{pw}}$$

where Q_d is the flow rate of spent dialysate including any ultrafiltration, and C_{d0} and C_{pw} represent values of the initial dialysate urea concentration and the predialysis plasma water concentration respectively. Nevertheless, according to the invention, we are only interested in the *ratio* between K_{wb} and K_{eff}. Therefore, the plasma water concentration C_{pw} can be

eliminated, and no blood sample is required. Thus, provided that we know the dialysate flow rate Q_d, the clearance ratio K_{wb}/K_{eff} may be calculated by the processor 212 in the figure 2 as:

$$\frac{K_{wb}}{K_{eff}} = \frac{K_{wb}}{V} \cdot \frac{m_0}{Q_d \cdot C_{d0}}$$

Figure 3 is a graph over a removal rate function C_d (or C_b) describing an example of how a urea concentration is lowered in the dialysate (or in the blood) during the dialysis treatment. In case the curve describes the dialysate urea concentration, an initial urea concentration C_{d0} may be found from the urea curve in the urea monitor (see e.g. 211 in figure 2), by fitting an exponential 310 to the function during an initial phase of the treatment t_1 to t_2, say 5 - 20 minutes at the beginning of the treatment. Of course, a graph describing the removal rate function C_b on the blood side actually starts at a non-zero initial urea concentration C_{b0}, at say twice the illustrated C_{d0}-value. However, this part of the graph is not shown here.

On the dialysate side, the exponential 310 is extrapolated backwards to the start (i.e. t=0) to find the initial dialysate urea concentration value C_{d0}. It generally takes about 5 minutes for the urea monitor 211 to find correct values at the start of the treatment, and this delay means that the dialysate urea C_{d0} found by the proposed method is a value which corresponds to a fully developed cardiopulmonary recirculation. The initial blood urea concentration C_{b0} is, on the other hand, most easily determined by means of a predialysis blood sample.

Figure 4 shows a flow diagram which illustrates the general method of estimating a process efficiency of a dialysis system according to the invention.

One step 410, involves performing a dialysis treatment of a specific patient. Another step 420, which is partly executed before and partly executed in parallel with the step 410, involves determining a whole body clearance ratio for the patient ac-

cording to the above-proposed method. Although, of course, the dialysis treatment of the step 410 continues until the treatment is finished, the determination in the step 420 may be completed at an earlier point in time after which the procedure ends.

Figure 5 shows a flow diagram which illustrates the general method of estimating a whole body clearance ratio of a dialysis treatment of a patient according to the invention.

A first step 510 determines an initial dialysate urea concentration C_{d0}. Then, a step 520 determines a total flow rate Q_d of spent dialysate during the treatment, including any ultrafiltration. During a steady state phase of the treatment, measurements are performed reflecting the rate at which a dialysate urea concentration is lowered in course of the treatment. Specifically, a step 530 calculates a slope K_{wb}/V of a logarithmic removal rate function, which describes the dialysate urea concentration over time. Subsequently, a step 540 determines a predialysis urea mass m_0 in the patient (for example according to the procedure proposed in US 6,258,027). Finally, a step 550 determines the whole body clearance ratio K_{wb}/K_{eff} as the product of the slope K_{wb}/V calculated in the step 530 and the predialysis urea mass m_0 (of the step 540), divided by the initial dialysate urea concentration C_{d0} (determined in the step 510) and the flow rate Q_d (determined in the step 520).

Returning now to figure 3, during a steady state phase of the treatment t_3 to t_4, say one hour or at least half an hour after the beginning of the treatment and onwards, a slope K_{wb}/V of the logarithm of the dialysate concentration is calculated. As already mentioned above with reference to the figure 3, the slope K_{wb}/V of the logarithm of the concentration may be measured on the dialysate side or on the blood side using at least two blood samples which are well spaced in time. The entire distribution volume V may be measured separately, and by multiplying the slope K_{wb}/V with the volume V, the whole body clearance K_{wb} can be obtained. The clearance ratio is then determined by

dividing K_{wb} by K_{eff} or K.

A straightforward way to measure the effective clearance K_{eff} or dialyzer clearance K is to register a removal rate (either on the blood side or on the dialysate side) and divide the registered figure by the systemic (or mixed blood venous) urea concentration C_{mv} or dialyzer inlet concentration C_b respectively.

Otherwise, the effective clearance K_{eff} may be measured by means of conductivity based methods, such as those described in the documents EP 547 025, EP 658 352 and US 6,217,539. Alternatively, the dialyzer clearance K may be found from the dialyzer data sheet.

There are many ways to determine the entire distribution volume V. One possibility is to collect a part of the spent dialysate, from which removed urea is determined from the urea concentration multiplied by the total dialysate volume. After correction for urea generation, this measure is related to the change in the equilibrated blood urea concentration with a correction for ultrafiltration. The entire distribution volume V multiplied by the change in the corrected equilibrated blood concentration must equal the removed amount. This gives a value for the volume V.

Yet another possibility to obtain the clearance ratio is to measure the ratio between the final blood urea concentration shortly after the end of the treatment, and the equilibrated concentration C_{eq} after half an hour to one hour, i.e. measure the urea rebound. If the final blood urea concentration directly after the end of the treatment is used, the figure reflects the ratio K_{wb}/K, since the effect of the cardiopulmonary recirculation will be included. If instead, a final blood urea concentration is used, which is measured about one minute after the end of the treatment, the figure reflects the ratio K_{wb}/K_{eff} because then the effect of the cardiopulmonary recirculation has disappeared.

It should be noted that the actual equilibrated concentration C_{eq} must be measured for the ratio calculation. For instance, it is not

sufficient to calculate the equilibrated concentration C_{eq} from the final concentration and the treatment efficiency (as suggested by Daugirdas), or to measure the concentration about 35 minutes before the end of the treatment (as suggested by Tattersall). Namely, these strategies will only provide a mean effect over a plurality of patients, not the effect with respect to each particular patient.

Another possibility is to study the urea concentration in the spent dialysate. This concentration shows a two-pool behavior. After the initial half hour to one hour the concentration follows a single exponential, whereas a first part of the curve is better described as a sum of this exponential and another exponential (which fades away more rapidly). Hence, these two exponentials may be used to characterize the patient with respect to the clearance ratio.

Referring to figure 6, an alternative to the above-described methods is to calculate the clearance ratio K_{wb}/K from concentrations in three blood samples. A first sample C_{b0} is taken just at the start of the treatment (i.e. t=0). A second sample C_{mid} is taken at t_{mid}, at least half an hour to an hour into the treatment, after the gradient between the two body pools has developed. A third and final sample C_{last} is taken at t_{last} towards the end of the treatment. The logarithm of the two values C_{mid} and C_{last} are used to extrapolate linearly backwards to the start of the treatment in order to find what the initial concentration would have been if the gradient between the body pools had been fully developed already at the start. This value is then divided by the actual initial value obtained from the first sample C_{b0} to find the clearance ratio K_{wb}/K. Consequently, the clearance ratio K_{wb}/K is calculated as:

$$\frac{K_{wb}}{K} = \frac{C_b}{C_{eq}} = \frac{C_{last}}{C_{b0}} \cdot \left(\frac{C_{mid}}{C_{last}} \right)^{\frac{t_{last}}{t_{last} - t_{mid}}}$$

Below follows examples, which further elucidate the invention, by studying the relation between whole body clearance and effective blood water clearance for urea. Effective blood water clearance can be measured through the dialyzer effect on a step in the inlet conductivity. It is called effective because it takes into account the effect of recirculation, both cardiopulmonary and in the access. This has led to the misconception that this clearance also describes the total cleaning effect of the dialysis treatment. The differences between the two clearance definitions are important for dose calculations, and can also be used to explain differences between patients. To continue, we need to discuss the clearance definitions, and we will use the regional blood flow model for this purpose. The examples are described with reference to figures 7 to 24.

As shown in figure 7, in this model we have one small pool of volume V_H, corresponding to internal organs that are perfused by a high rate blood flow Q_H. The large pool with volume V_L is perfused by the low rate blood flow Q_L. The heart-lung system is lumped together, and blood with a urea concentration C_b enters the dialyzer.

Referring now to figure 8, since the high flow pool will be more effectively cleaned, its concentration C_H will always be lower than the low flow pool concentration C_L. The mixed venous concentration C_{mv} coming back to the heart-lung system from the body is a result of the two pool concentrations being weighted together according to the flows Q_H and Q_L. C_{mv} must therefore lie in between C_H and C_L, and it will be closer to C_H because of the heavier weight from the high flow Q_H.

As depicted in Figure 9, in order to measure the depuration of the whole body the equilibrated concentration C_{eq} is more relevant than C_{mv}. C_{eq} is also a weighted mean value of the pool concentrations, but with their volumes as weighting factors, which makes a big difference. Just as C_{mv}, C_{eq} will also fall in

between C_H and C_L, but it will be closer to C_L because of the heavier weight from the large low flow pool volume V_L.

Then, in figure 10, we have this order between the different concentrations, with C_b lowest as a result of mixing C_{mv} with cleaned blood from the dialyzer. Since clearance is removal rate divided by concentration, we could have five different clearance values. C_H and C_L are of course less interesting, but the other three all have meaningful interpretations.

As defined in figure 11, the first one, which involves the blood concentration entering the dialyzer, is the normal dialyzer clearance that is used to characterize different dialyzers. If we use the mixed venous concentration we get the effective clearance, which will include the effects of both cardiopulmonary and access recirculation. This can be measured by conductivity methods such as OnLine Clearance from Fresenius and Diascan from Gambro. Finally we have the whole body clearance, which can also be called equilibrated clearance, and results if we use the equilibrated concentration. Because of the relation between the concentrations, we will always have this relation between the clearances, and our aim was to study the relation between the two last ones, both clinically and theoretically. So, how did we measure these clearances?

In figure 12, the effective clearance K_{eff} was measured in two different ways.

Figure 13 presents clearance by conductivity. Firstly, using a step in the inlet conductivity of the dialysis fluid, clearance was calculated in the Integra dialysis machine from the decrease in the dialyzer of the conductivity step size. This is known to give an estimate of the effective plasma water clearance.

Secondly, as shown in figure 14, clearance was calculated from the dialysate flow rate and the initial urea concentrations in the dialysate and in plasma water. The dialysate concentration was measured continuously in the spent dialysate by a urea monitor.

The initial concentration was determined by fitting an exponential 5-20 minutes from the start, which was then extrapolated backwards. This calculation will give the effective clearance since the dialysate concentration after 5 minutes will refer to a fully developed cardiopulmonary recirculation, whereas the pre-treatment blood sample gives the systemic blood urea concentration.

Then, shown in figure 15, the whole body urea clearance is obtained from the mass based urea kinetics that have been described elsewhere. This is a logarithmic plot of dialysate urea, and the negative steady state slope will be whole body K/V. From the slope and the removal rate it is possible to calculate mo, the predialysis urea mass in the body, and by definition this is equal to the product of volume and plasma water concentration. (Whole body Kt/V has been shown to agree with equilibrated Kt/V, and the volume V with volume determined by dialysate collection and DDQ, Direct Dialysate Quantification.)

Also, as in figure 16, the whole body clearance can then be calculated as the product of the slope and the urea mass, divided by the plasma water concentration.

Then, in particular as shown in figure 17, we studied the relation between whole body clearance and effective clearance in 80 treatments of 20 patients. A urea monitor in the spent dialysate was used to calculate whole body clearance about one hour into the treatment. An Integra machine was used for 42 treatments and a Cobe C3 machine for the remaining 38. Effective clearance was calculated from the initial concentrations, but the conductivity-based clearance could be measured only in the Integra treatments. 9 treatments had to be discarded due to fistula recirculation or technical problems.

With reference to figure 18, we see a graph over the 35 remaining Integra treatments, where the whole body clearance is about 11% lower than the conductivity based clearance. But the

data are fairly scattered, and we would therefore like to compare the whole body clearance with the initial effective clearance based on urea concentrations instead.

As shown in figure 19, this can be done since conductivity based clearance and initial effective clearance agree quite well as shown in this diagram from our study. This agreement has also been shown by several previous studies.

Referring to figure 20, if we now compare the whole body clearance to initial effective clearance based on urea concentrations in all remaining 71 treatments we see that the data are much less scattered. The difference is still about 11 %. The next figure shows the ratio between these two clearances.

Then in figure 21, the ratio is shown as a function of the relative treatment efficiency, whole body K/V, and we see that there is a negative correlation. This corresponds to the correlation between K/V and the error in single pool Kt/V that is the basis for Daugirdas' rate equation.

Next, in figure 22, if we look at the clearance ratios for each patient, we see that there is a clear difference between patients. Shown here are the range and median value for each patient, and the patients have been ordered according to median value. We see that the clearance ratio varies between roughly 0.8 and 0.95. For most patients the variation in ratio is less than the interpatient variation.

Referring now to figure 23, let us now go back and try to explain a theoretical basis for the ratio variations. Again the two-pool regional blood flow model will be used, and in the simplified analysis it is assumed that there is no ultrafiltration or urea generation. It is then possible to set up a differential equation describing the evolution of the ratio of the two pool concentrations, which shows that their ratio will fairly quickly approach a steady state value. This is all that is needed to calculate the steady state ratio between whole body clearance and effective

clearance. The clearance ratio will depend on the ratio of the two volumes, the ratio of the two flows, and the ratio of the effective clearance to the systemic blood flow.

Referring to figure 24. Shown here is the theoretical clearance ratio as a function of the effective clearance for a systemic blood flow of 5 L/min, a low flow pool volume of 80% of the total volume, and a flow fraction to this pool of 10, 20 and 30% of the total systemic flow. This range of parameters agrees with what Daugirdas and Schneditz found necessary to explain observed urea rebound. In our study the clearances were slightly above 200, and we see that the theoretical ratio variation is between 0.8 and 0.95, which agrees well with the clinical results. We also see that at higher clearances between 300 and 400, whole body clearance can be as much as 30% or more below the effective clearance, but the actual ratio depends heavily on the patient parameters.

The following conclusions can be drawn. Effective clearance by conductivity overestimates whole body clearance in a patient dependent way. Last, but not least, in patients with a large gap between whole body clearance and effective clearance (i.e. a small ratio) there seems to be a large potential for efficiency improvements by affecting the patient parameters. The big question is how this could be achieved.

The term "comprises/comprising" when used in this specification is taken to specify the presence of stated features, integers, steps or components. However, the term does not preclude the presence or addition of one or more additional features, integers, steps or components or groups thereof.

The invention is not restricted to the described embodiments in the figures, but may be varied freely within the scope of the claims.

Claims

1. A method of estimating a process efficiency of a dialysis system comprising a dialyzer (130) and a patient (120), where the patient's blood system is connected to the dialyzer (130) such that the dialyzer (130) performs a dialysis treatment of the patient (120), the dialyzer (130) having a potential cleaning capacity (K_{eff}, K), **characterized by** the step of:

determining a whole body clearance ratio (K_{wb}/K_{eff}, K_{wb}/K) which expresses how well the patient (120) responds to the potential cleaning capacity (K_{eff}, K).

2. A method according to claim 1, **characterized by** determining the whole body clearance ratio (K_{wb}/K_{eff}, K_{wb}/K) by:

measuring a final blood urea concentration no later than approximately one minute after the end of the treatment,

measuring an equilibrated blood urea concentration no earlier than approximately one half hour after the end of the treatment, and

dividing said final blood urea concentration by said equilibrated blood urea concentration.

3. A method according to claim 2, **characterized by** measuring the final blood urea concentration directly after the end of the treatment to obtain the whole body clearance ratio (K_{wb}/K) in respect of a dialyzer clearance (K).

4. A method according to claim 2, **characterized by** measuring the final blood urea concentration approximately one minute after the end of the treatment to obtain the whole body clearance ratio (K_{wb}/K_{eff}) in respect of an effective clearance (K_{eff}).

5. A method according to claim 1, **characterized by** determining the whole body clearance ratio (K_{wb}/K_{eff}, K_{wb}/K) by:

measuring an initial urea concentration (C_{d0}; C_{b0}),

measuring, during the treatment at occasions being well spaced in time at least two subsequent urea concentration values after the treatment has started, a first value of said at least two values being measured no earlier than approximately one half hour after the treatment has started,

deriving a starting urea concentration based on an extrapolation in time of said at least two values back to the start of the treatment, and

dividing said starting urea concentration by said initial urea concentration (C_{d0}; C_{b0}).

6. A method of estimating a whole body clearance ratio (K_{wb}/K_{eff}) of a dialysis treatment of a patient (120), the whole body clearance ratio (K_{wb}/K_{eff}) expressing how well the patient (120) responds to a potential cleaning capacity (K_{eff}) of a dialyzer (130) which performs the treatment, **characterized by** determining the whole body clearance ratio (K_{wb}/K_{eff}) based on a measurement of a slope (K_{wb}/V) of a logarithmic removal rate function (C_d, C_b) which describes how a urea concentration is lowered in course of the treatment.

7. A method according to claim 6, **characterized by** the steps of:

determining an initial dialysate urea concentration (C_{d0}),

determining a total flow rate (Q_d) of spent dialysate during the treatment including any ultrafiltration,

calculating, based on measurements performed during a steady state phase (t_3 - t_4) of the treatment, the slope (K_{wb}/V) of said logarithmic removal rate function (C_d),

measuring a predialysis urea mass (m_0) in the patient (120), and

determining the whole body clearance ratio (K_{wb}/K_{eff}) as the product of said slope (K_{wb}/V) and said predialysis urea mass (m_0), divided by said flow rate (Q_d) and divided by said initial urea concentration (C_{d0}).

8. A method according to claim 6, **characterized by** the steps of:

calculating, based on measurements performed during a steady state phase (t_3 - t_4) of the treatment, the slope (K_{wb}/V) of said logarithmic removal rate function (C_d; C_b),

determining an entire distribution volume (V), and

determining the whole body clearance ratio (K_{wb}/K_{eff}; K_{wb}/K) as the product of said slope (K_{wb}/V) and said entire distribution volume (V) divided by the potential cleaning capacity (K_{eff}; K).

9. A method according to any one of the claims 7 or 8, **characterized by** performing the measurements of the slope (K_{wb}/V) of said logarithmic removal rate function (C_d) on a dialysate side of a dialysis system comprising the dialyzer (130) and the patient (120).

10. A method according to claim 8, **characterized by** performing the measurements of the slope (K_{wb}/V) of said logarithmic removal rate function (C_b) on a blood side of a dialysis system comprising the dialyzer (130) and the patient (120).

11. A computer program directly loadable into the internal memory of a computer, comprising software for controlling the steps of any of the claims 1 to 5 when said program is run on the computer.

12. A computer readable medium, having a program recorded thereon, where the program is to make a computer control the steps of any of the claims 1 to 5.

13. A computer program directly loadable into the internal memory of a computer, comprising software for controlling the steps of any of the claims 6 to 10 when said program is run on the computer.

14. A computer readable medium, having a program recorded thereon, where the program is to make a computer control the steps of any of the claims 6 to 10.

15. A method of performing a dialysis treatment program with respect to a patient (120) by means of a dialyzer (130), the program comprising repeated dialysis treatments, **characterized by**

performing a first dialysis treatment of the patient (120) under a first set of conditions which include at least one of a treatment time and a composition of the dialysate in the dialyzer (130),

estimating, in course of the first dialysis treatment, a whole body clearance ratio (K_{wb}/K_{eff}, K_{wb}/K) according to any of the claims 2 to 5, or any one of the claims 6 to 10,

comparing the whole body clearance ratio (K_{wb}/K_{eff}, K_{wb}/K) with a threshold ratio, and if the whole body clearance ratio (K_{wb}/K_{eff}, K_{wb}/K) is less than the threshold ratio

performing a dialysis treatment of the patient (120) after said first dialysis treatment under a second set of conditions which are different from the first set of conditions.

16. An apparatus (210) adapted to estimate a whole body clearance ratio of a dialysis treatment of a patient (120), the whole body clearance ratio expressing how well the patient (120) responds to a potential cleaning capacity of a dialyzer (130) which performs the treatment, the apparatus (210) comprising:

a urea monitor circuit (211) adapted to: determine an initial dialysate urea concentration (C_{d0}); determine a total flow rate (Q_d) of spent dialysate during the treatment including any ultrafiltration; measure, during a steady state phase (t_3 - t_4) of the treatment, a slope (K_{wb}/V) of a removal rate function which describes how a dialysate urea concentration is lowered in course of the treatment; and measure a predialysis urea mass (m_0) in the patient (120), and

a processor (212) adapted to determine the whole body clearance ratio (K_{wb}/K_{eff}) for the patient (120), the whole body

clearance ratio (K_{wb}/ K_{eff}) being determined as the product of said slope (K_{wb}/V) and said predialysis urea mass (m_0), divided by said flow rate (Q_d) and divided by said initial dialysate urea concentration (C_{d0}).

17. Use of the apparatus (210) according to the claim 16 for estimating a whole body clearance ratio of a dialysis treatment of a patient (120).

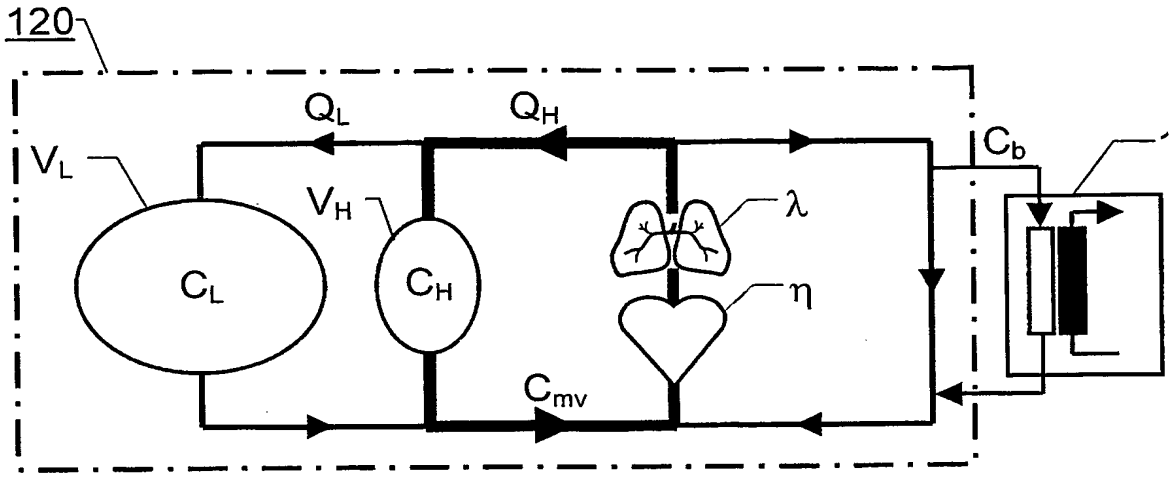


Fig. 1

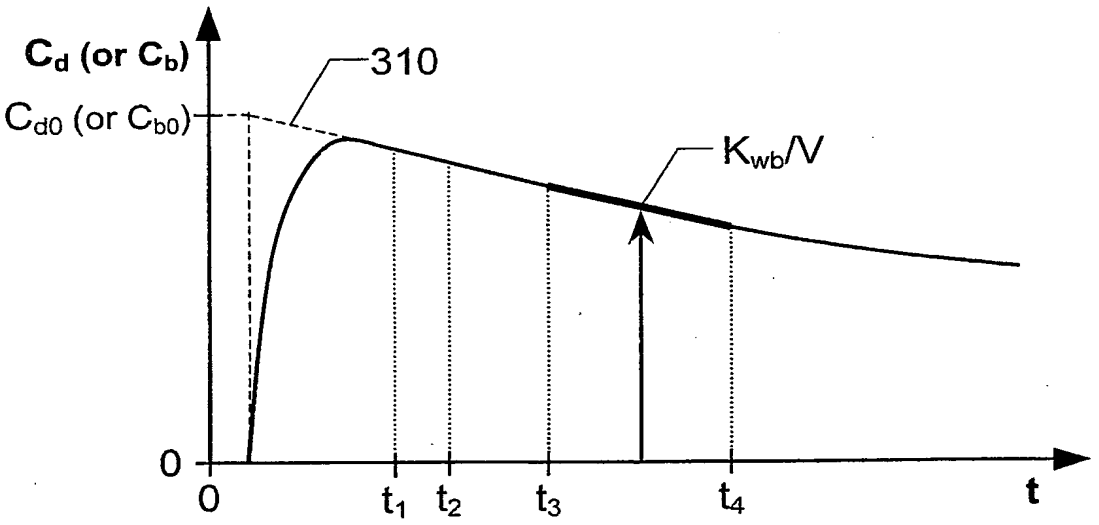


Fig. 3

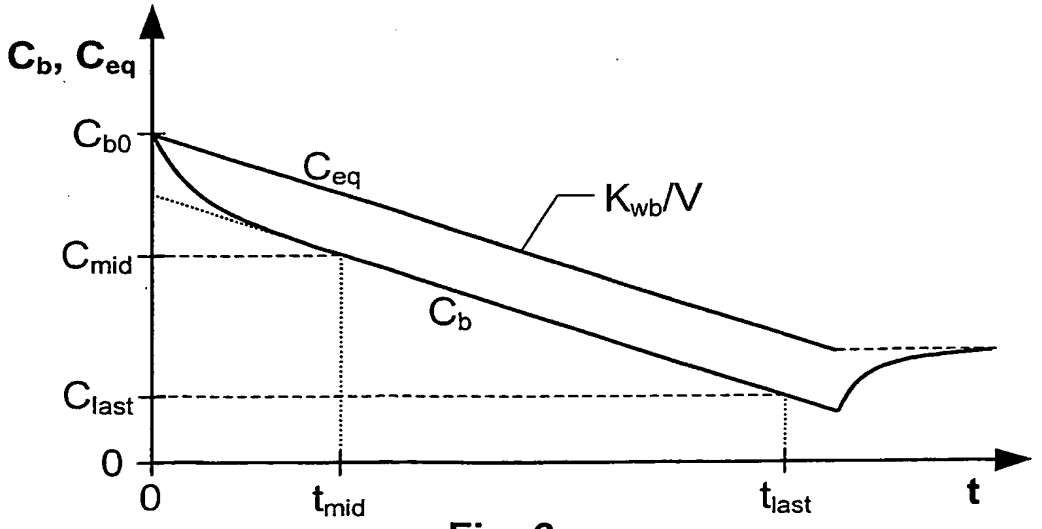


Fig. 6

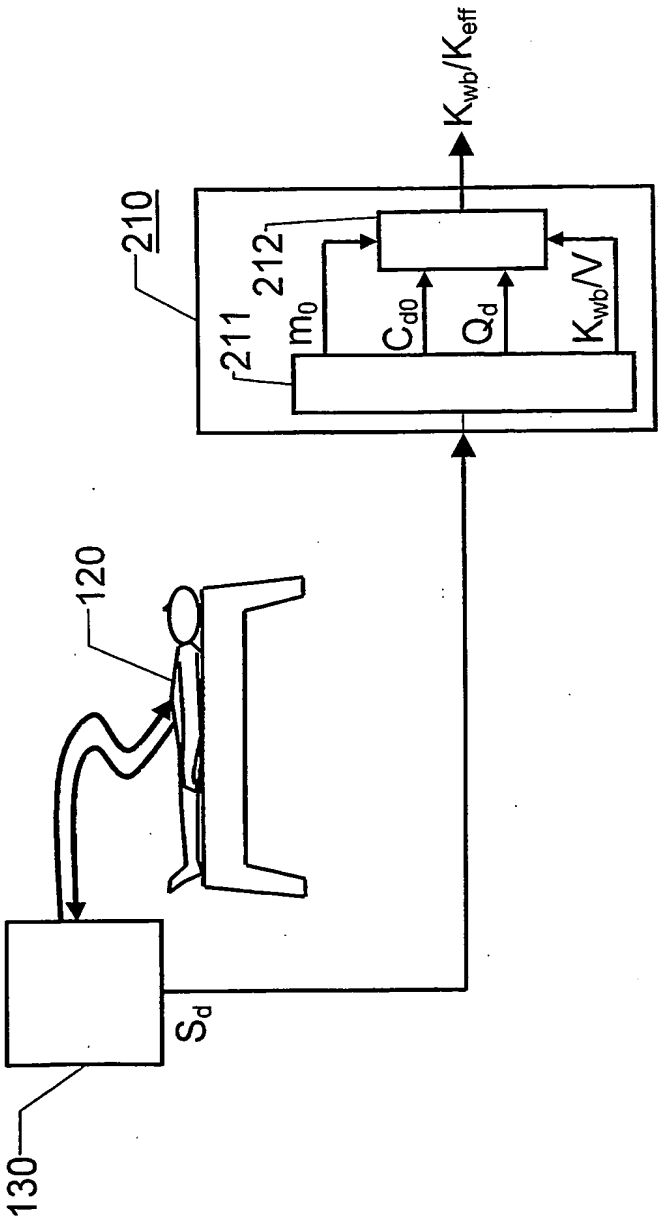


Fig. 2

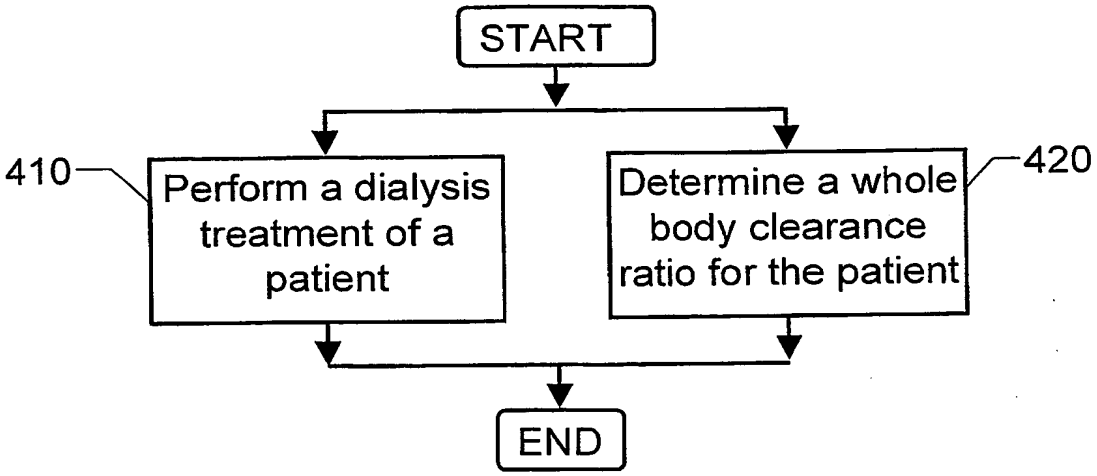

START
410
Perform a dialysis treatment of a patient
Determine a whole body clearance ratio for the patient
420
END

Fig. 4

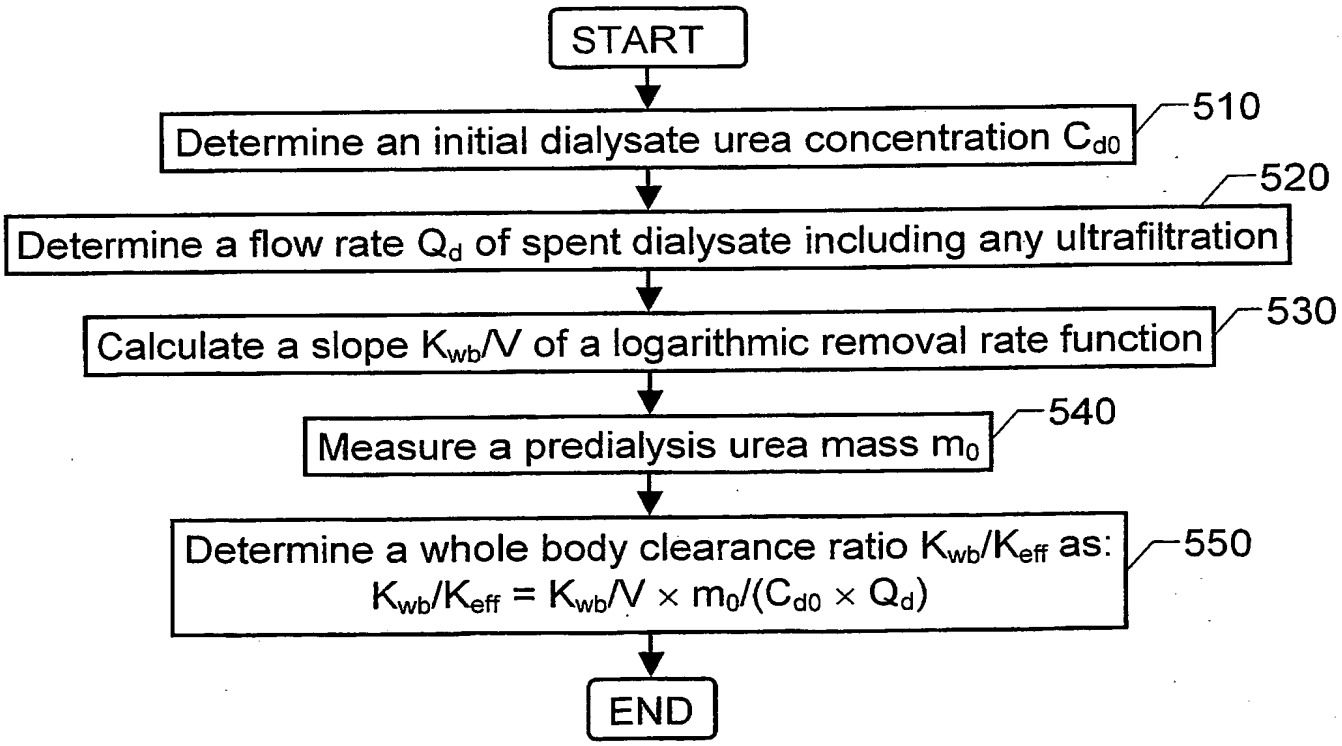

START
Determine an initial dialysate urea concentration C_{d0}
510
Determine a flow rate Q_d of spent dialysate including any ultrafiltration
520
Calculate a slope K_{wb}/V of a logarithmic removal rate function
530
Measure a predialysis urea mass m_0
540
Determine a whole body clearance ratio K_{wb}/K_{eff} as: $K_{wb}/K_{eff} = K_{wb}/V \times m_0/(C_{d0} \times Q_d)$
550
END

Fig. 5

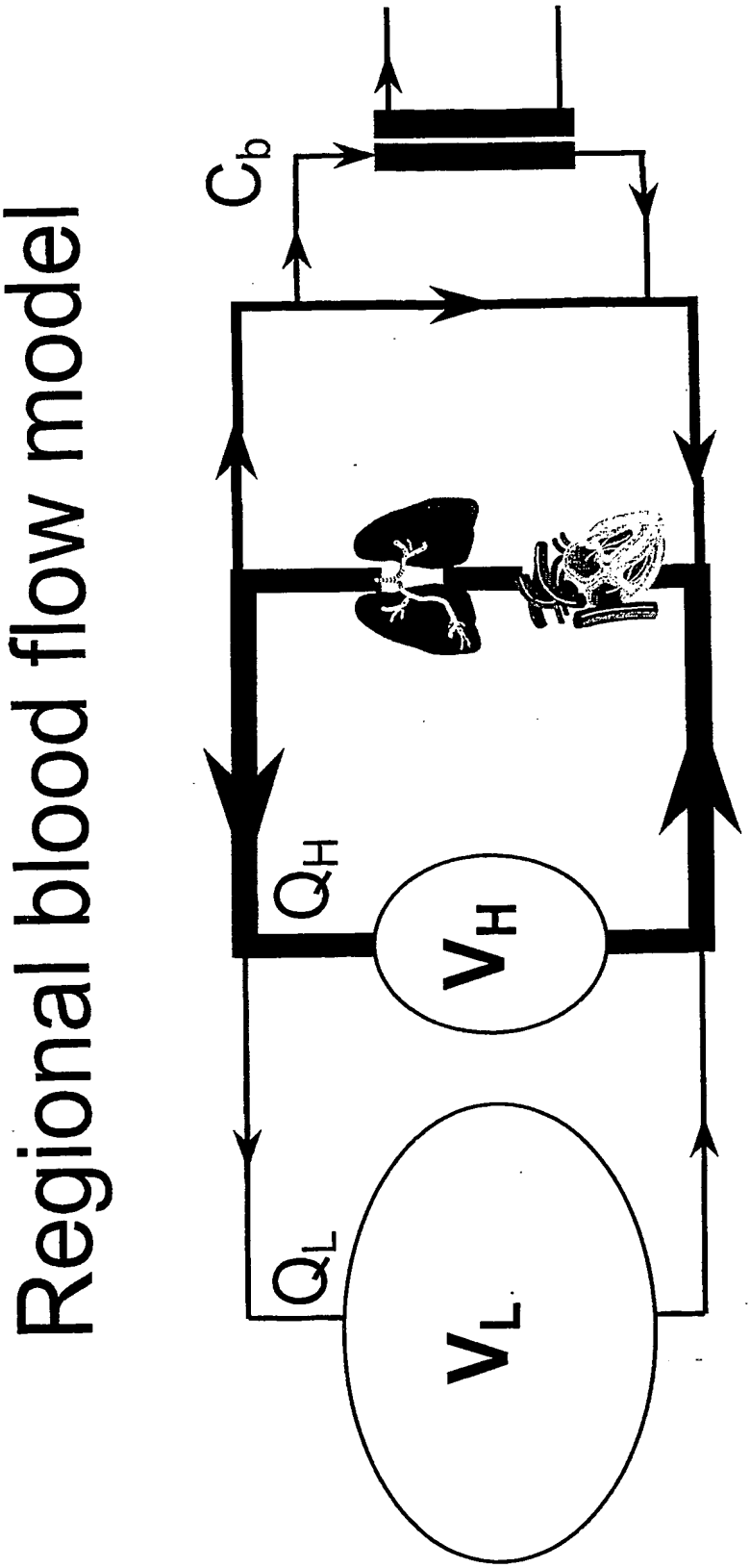
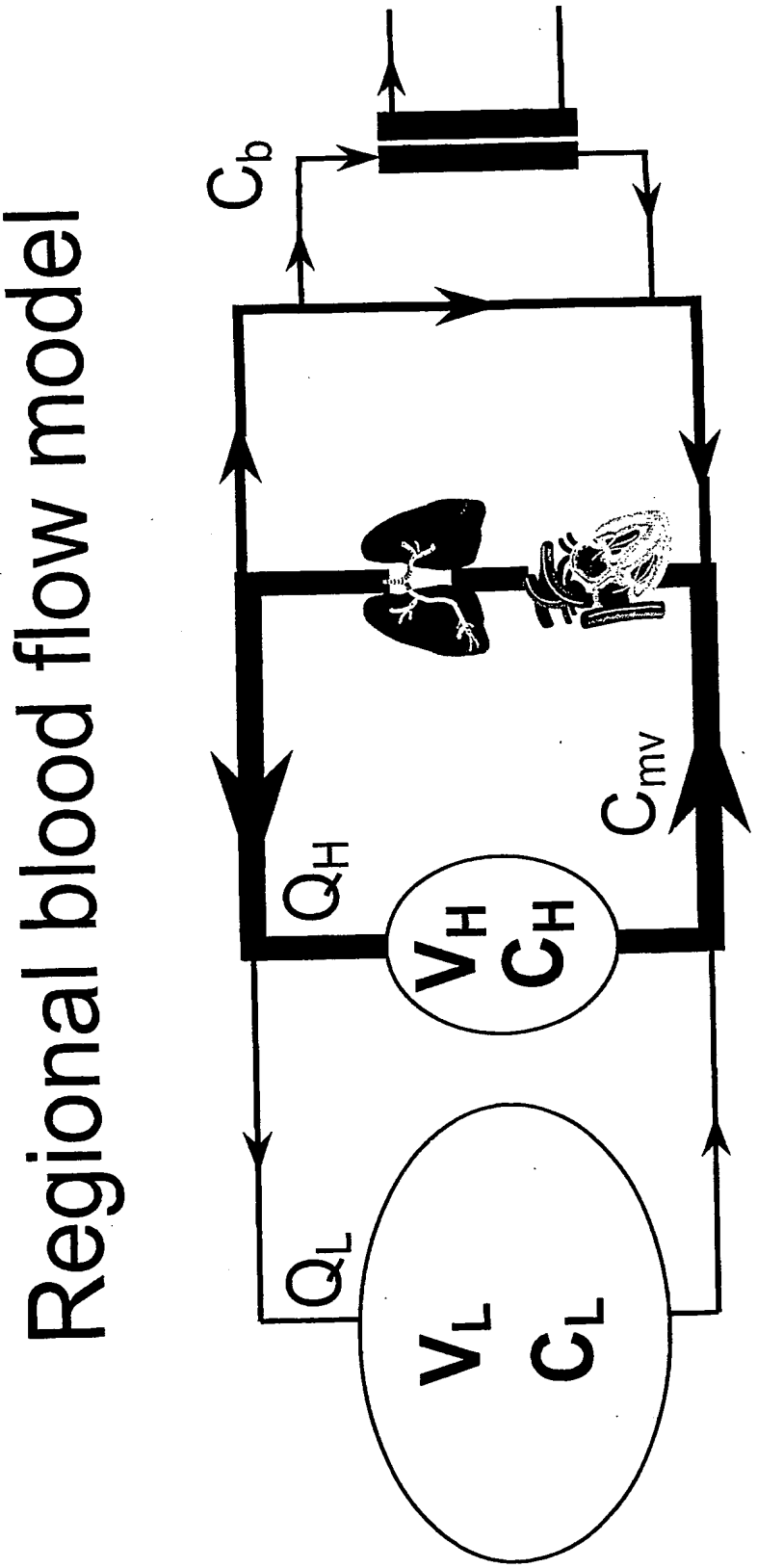
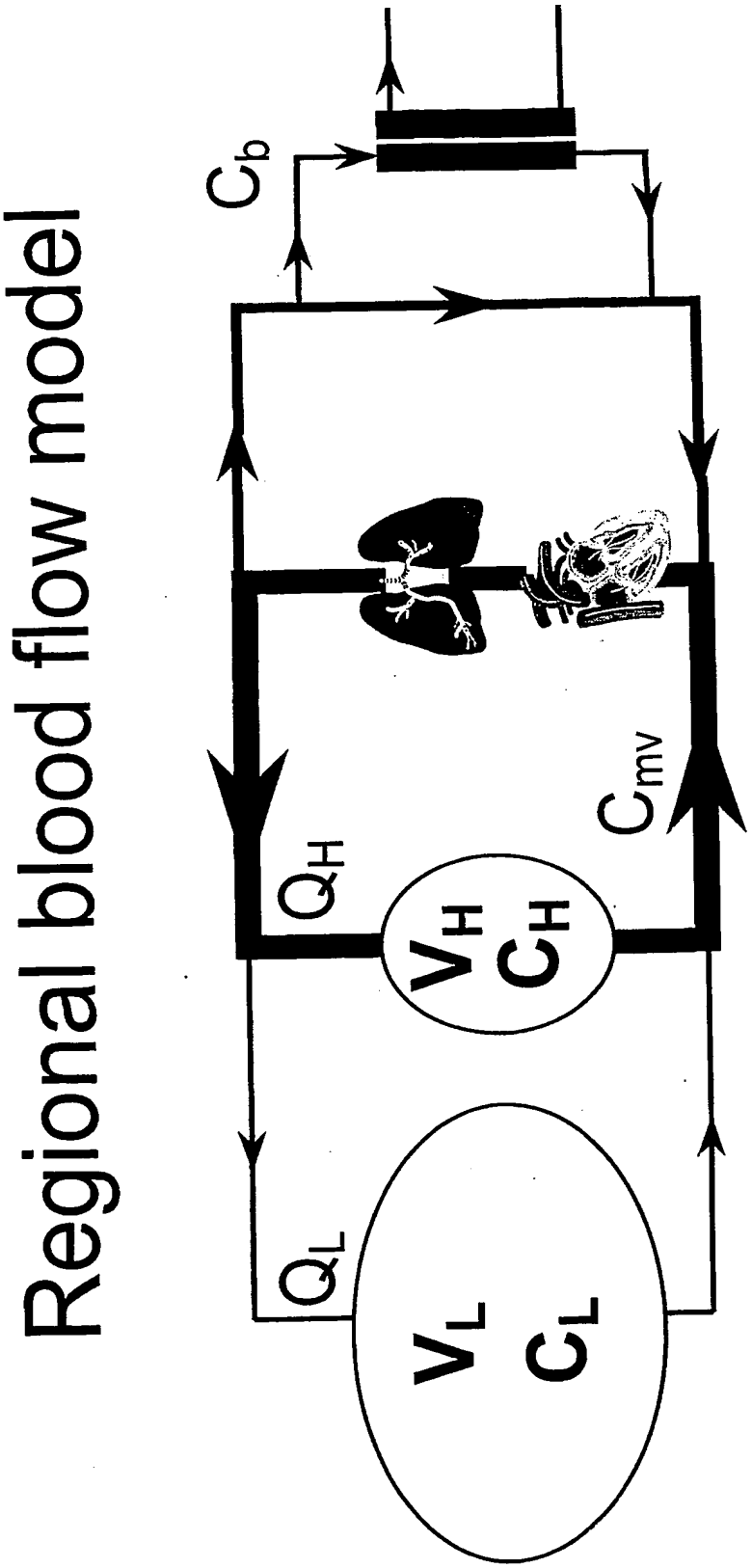


Fig. 7



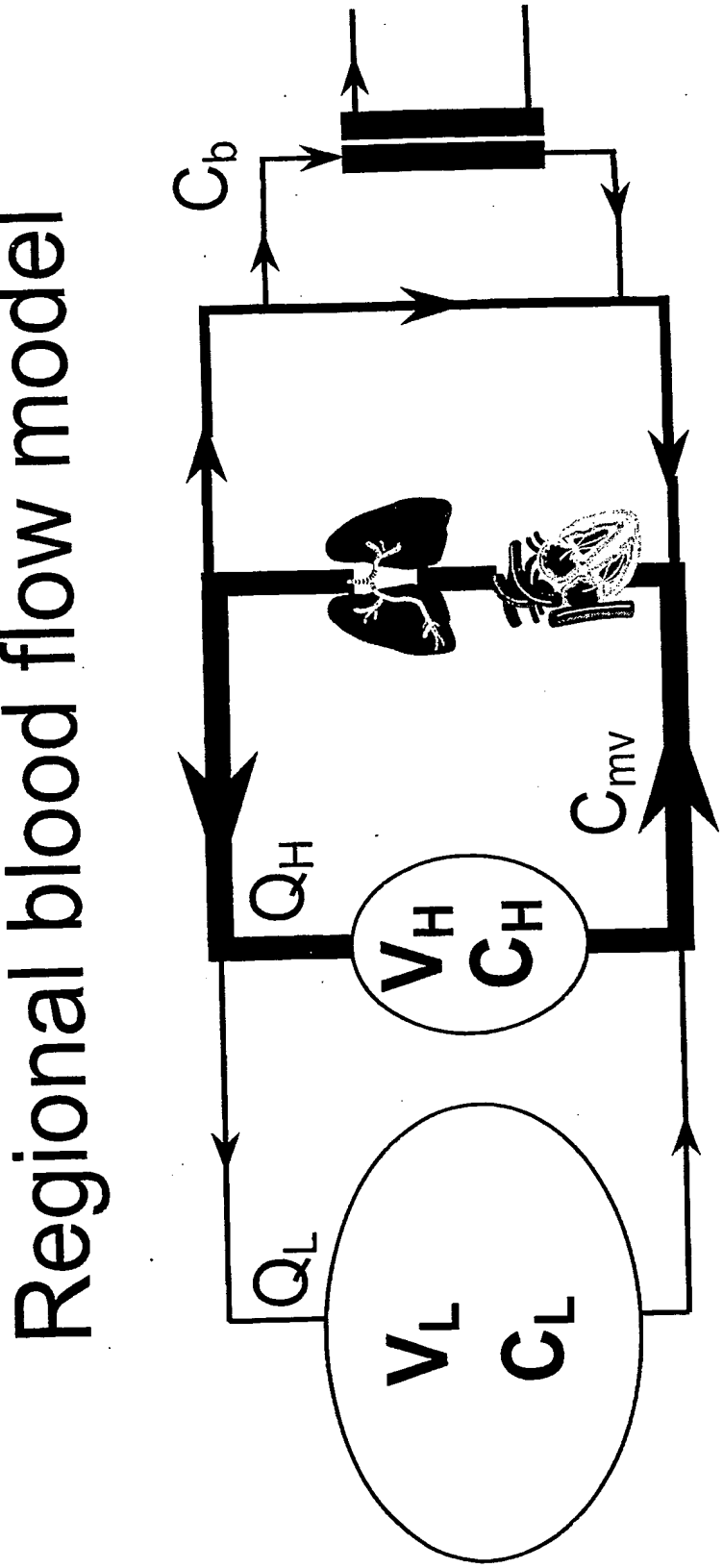
$$C_{mv} = \frac{Q_H \cdot C_H + Q_L \cdot C_L}{Q_H + Q_L}$$

Fig. 8



$$C_{mv} = \frac{Q_H \cdot C_H + Q_L \cdot C_L}{Q_H + Q_L} \qquad C_{eq} = \frac{V_H \cdot C_H + V_L \cdot C_L}{V_H + V_L}$$

Fig. 9



$$C_{mv} = \frac{Q_H \cdot C_H + Q_L \cdot C_L}{Q_H + Q_L} \qquad C_{eq} = \frac{V_H \cdot C_H + V_L \cdot C_L}{V_H + V_L}$$

$$\boxed{C_L > C_{eq} > C_{mv} > C_H > C_b}$$

Fig. 10

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Definitions of clearance

- Dialyzer clearance (In vivo) — K = removal rate / C_b
- Effective clearance (OnLine Clearance, Diascan) — Keff = removal rate / C_{mv}
- Whole body clearance (Equilibrated clearance) — Kwb = removal rate / C_{eq}

$$K > Keff > Kwb$$

Fig. 11

Measurement of effective clearance

- Through the effect of the dialyzer on a step in the inlet conductivity (Diascan)
- From the dialysate flow rate and the initial dialysate concentration together with the predialysis plasma water concentration

Fig. 12

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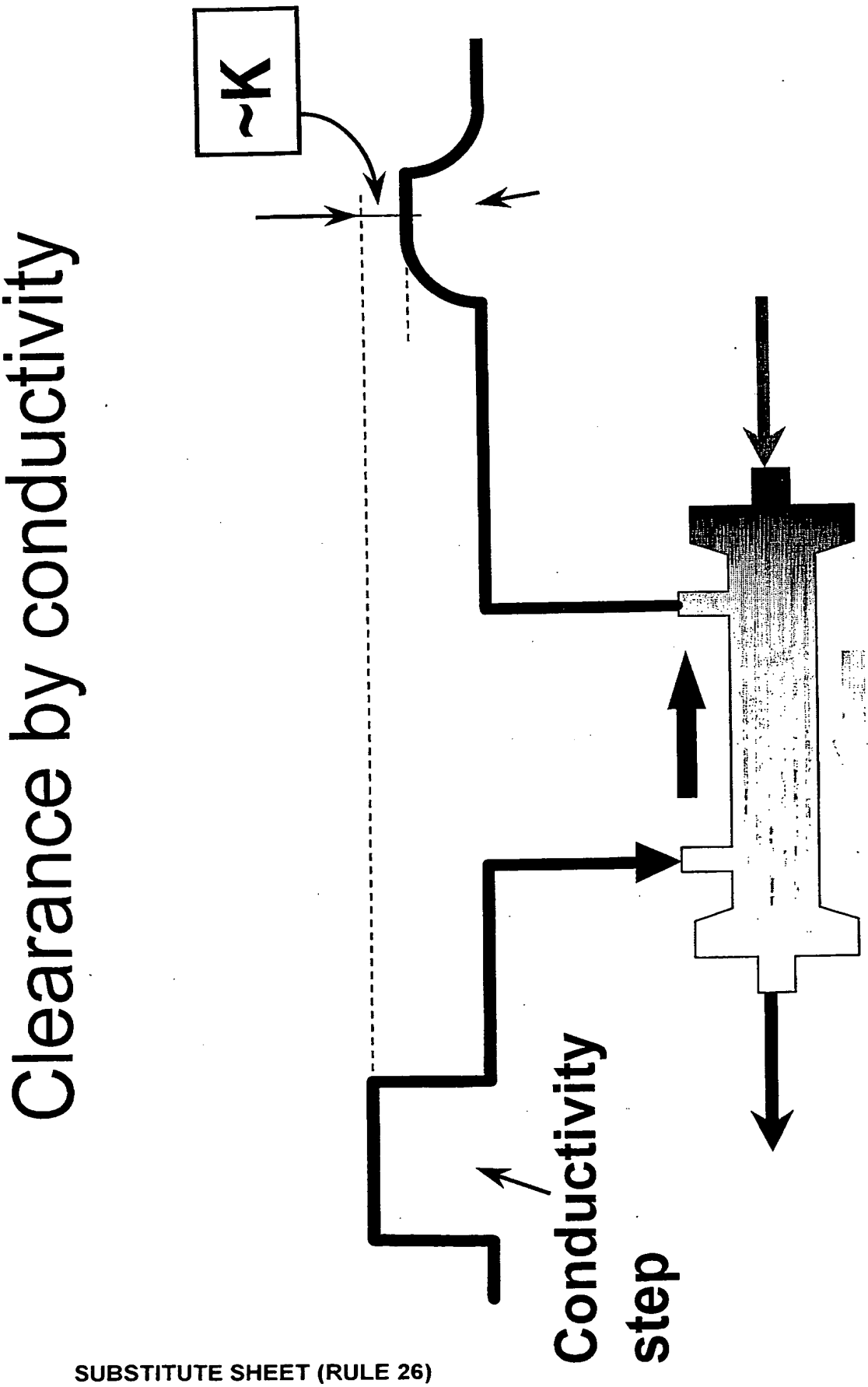

Fig. 13

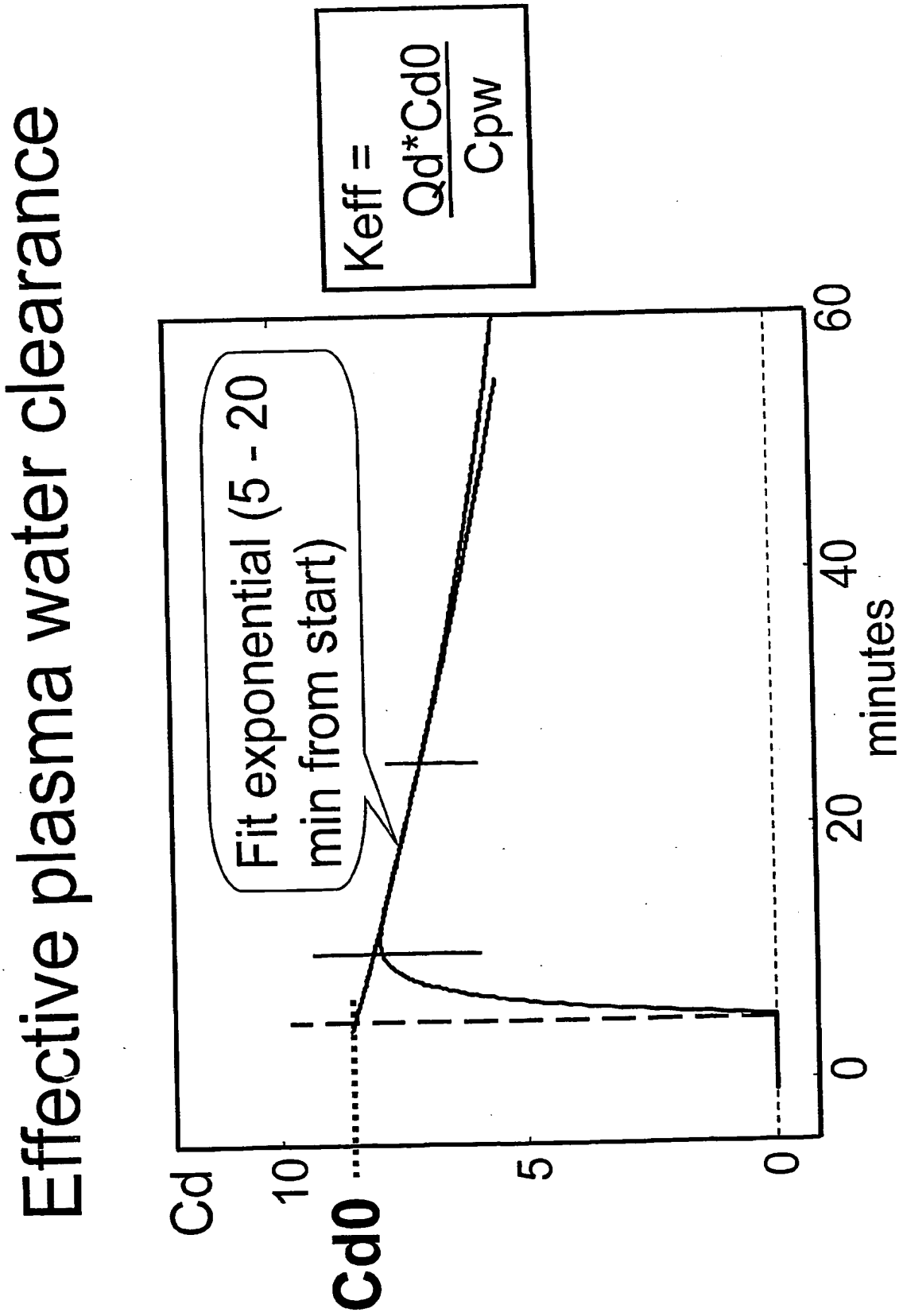
Effective plasma water clearance
Keff = Qd*Cd0 / Cpw
Fit exponential (5 - 20 min from start)
Cd
Cd0
10
5
0
0
20
40
60
minutes

Fig. 14

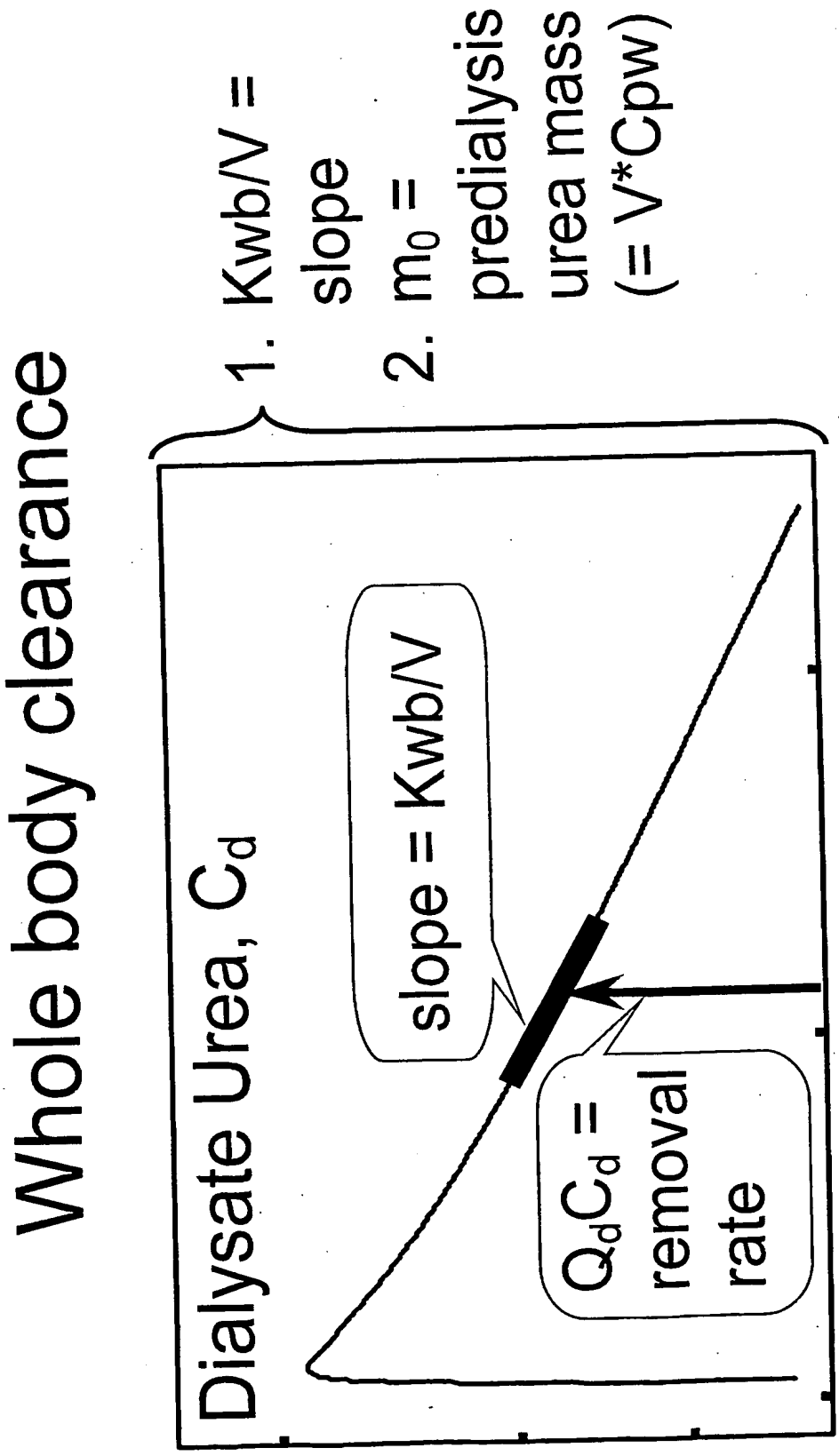
Whole body clearance
1. Kwb/V = slope
2. m_0 = predialysis urea mass (= V*Cpw)
Dialysate Urea, C_d
slope = Kwb/V
Q_dC_d = removal rate

Fig. 15

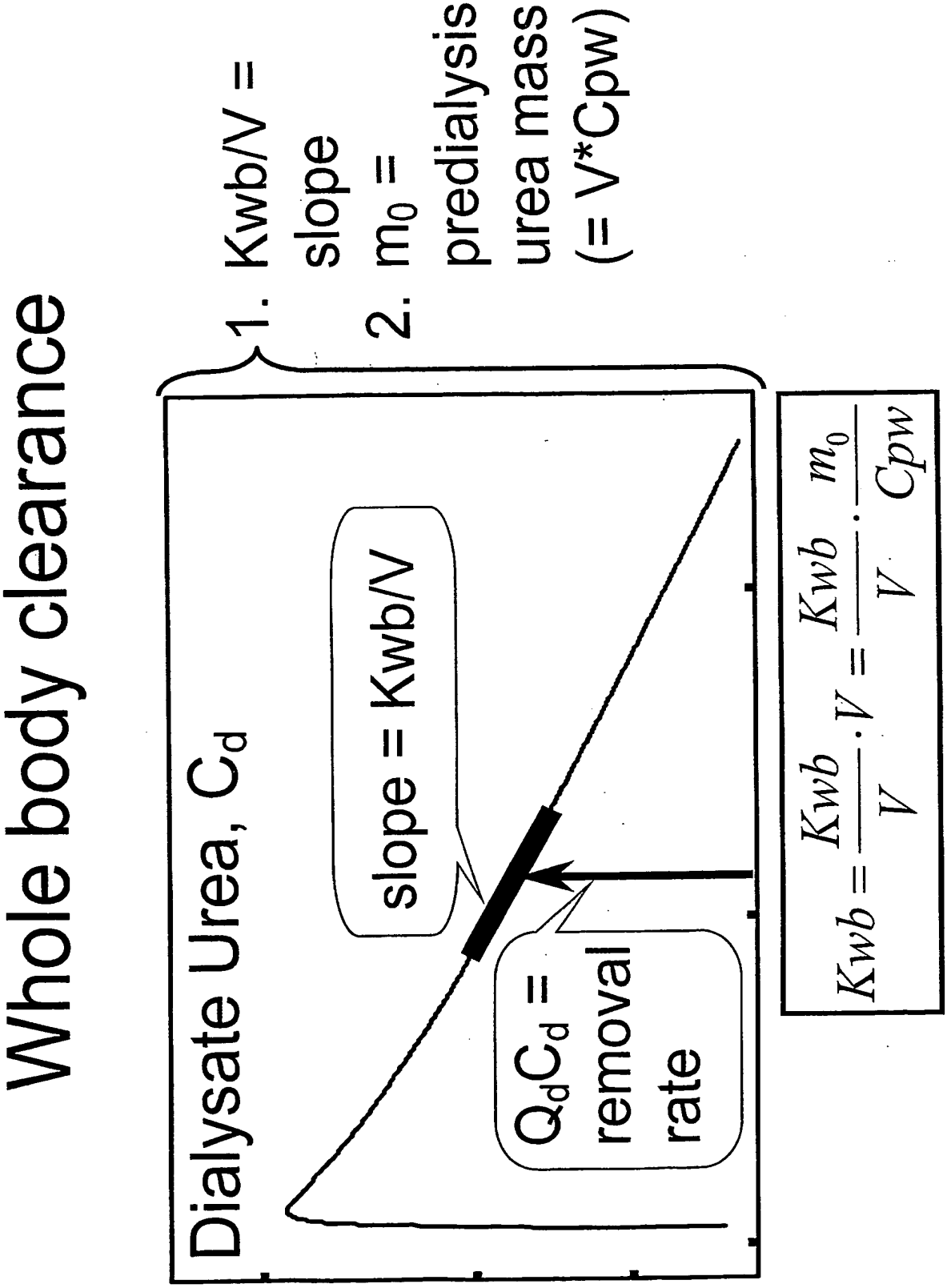
Whole body clearance
1. Kwb/V = slope
2. m_0 = predialysis urea mass (= V*Cpw)
Dialysate Urea, C_d
slope = Kwb/V
Q_dC_d = removal rate
$Kwb = \frac{Kwb}{V} \cdot V = \frac{Kwb}{V} \cdot \frac{m_0}{Cpw}$

Fig. 16

- 80 treatments of 20 patients (5 M/15 FM)
- Machines: Urea monitor (for Kwb) and
  - Integra (42) for Kcond and Keff
  - C3 (38) for Keff

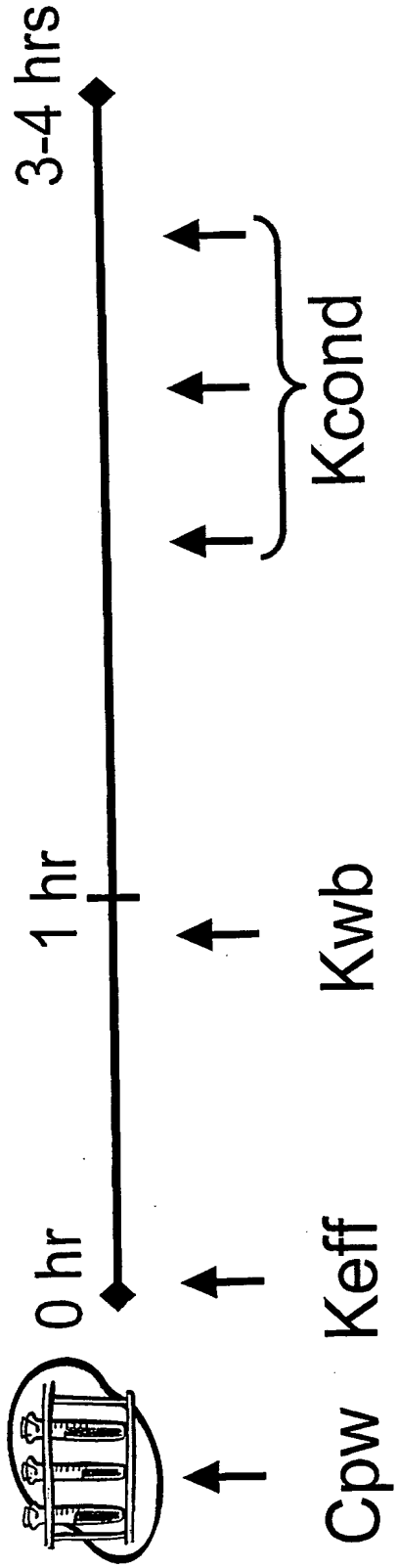

Fig. 17

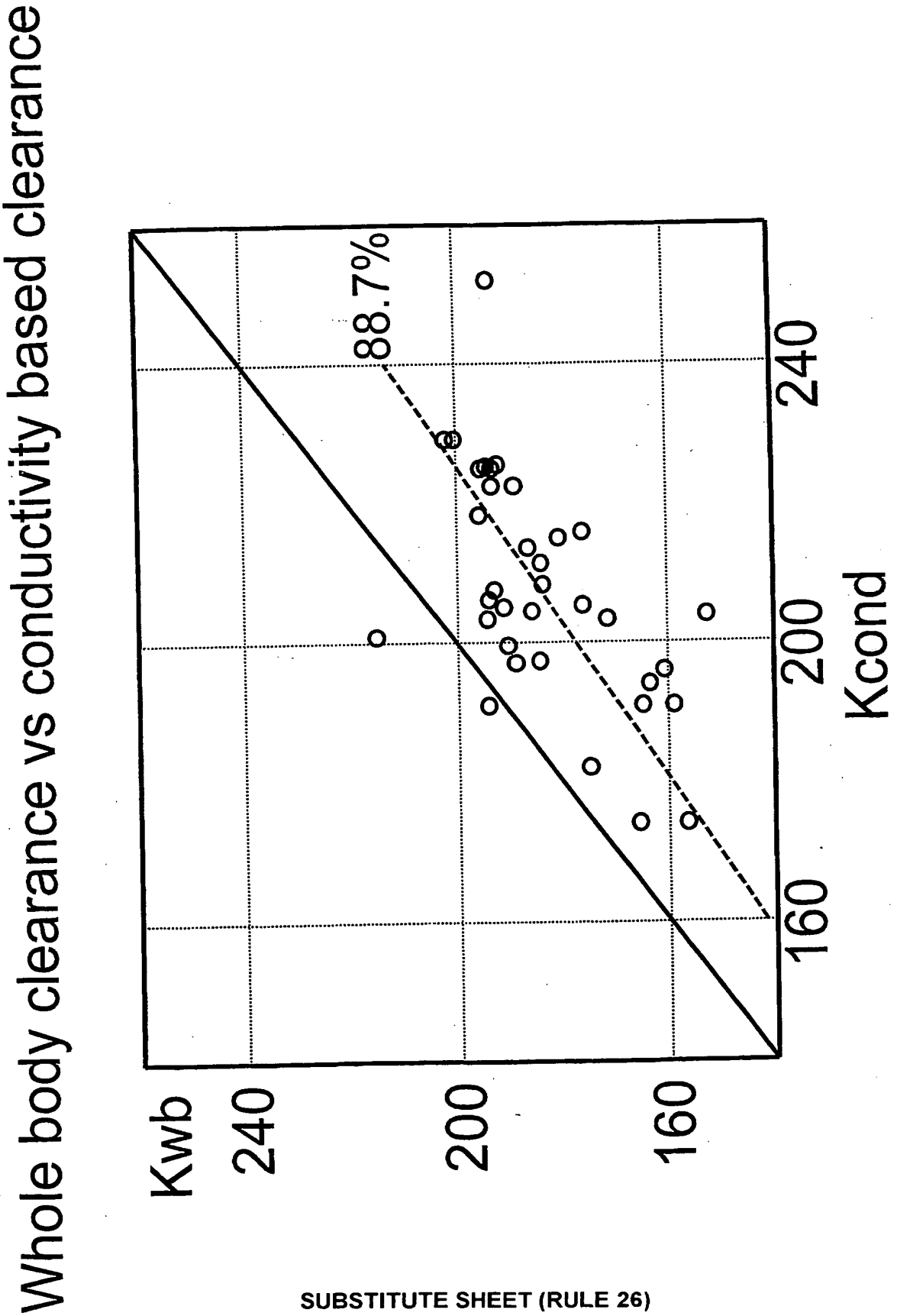
Whole body clearance vs conductivity based clearance
88.7%
Kwb
240
200
160
240
200
160
Kcond

Fig. 18

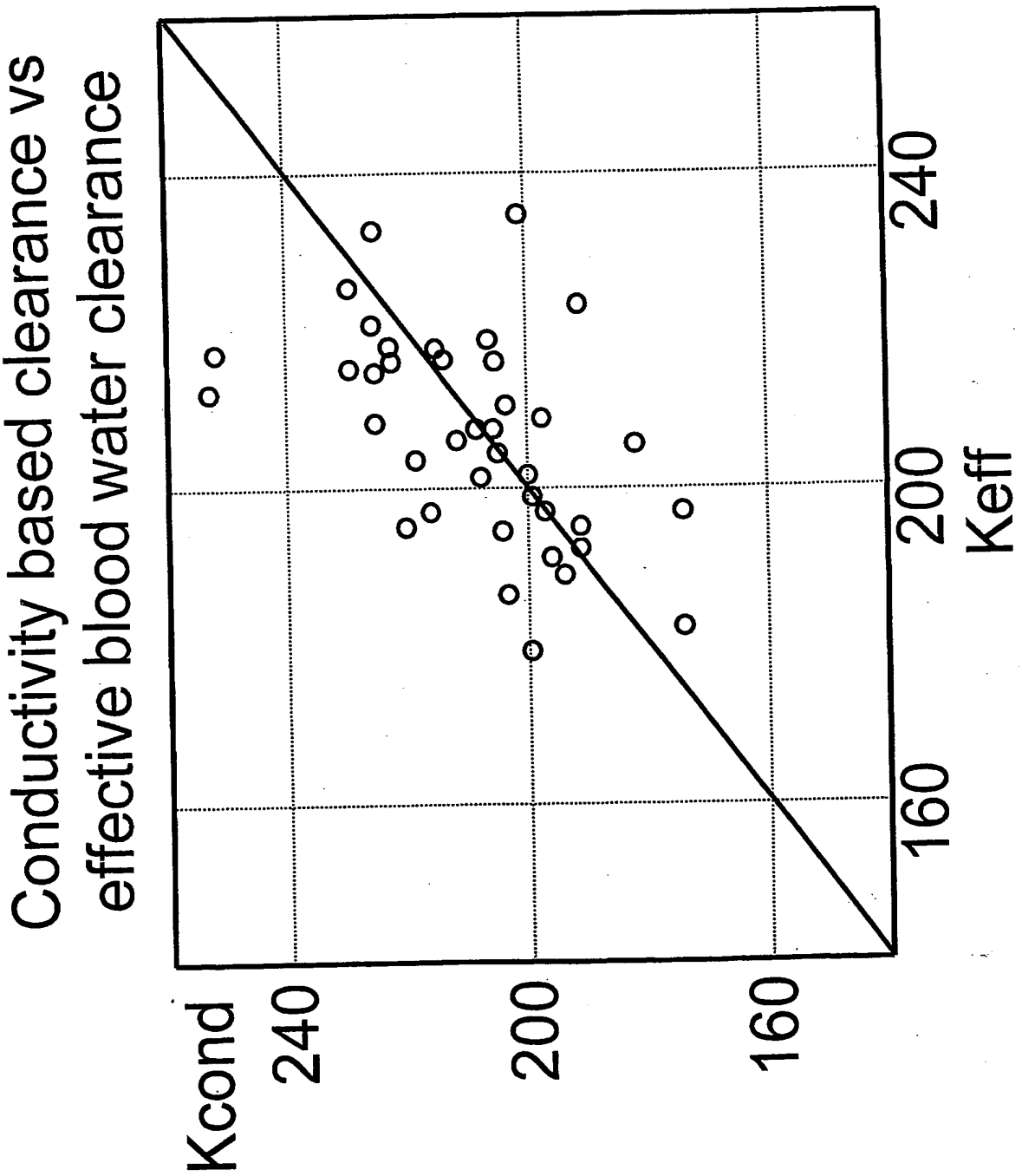
Conductivity based clearance vs effective blood water clearance
Kcond
240
200
160
240
200
160
Keff

Fig. 19

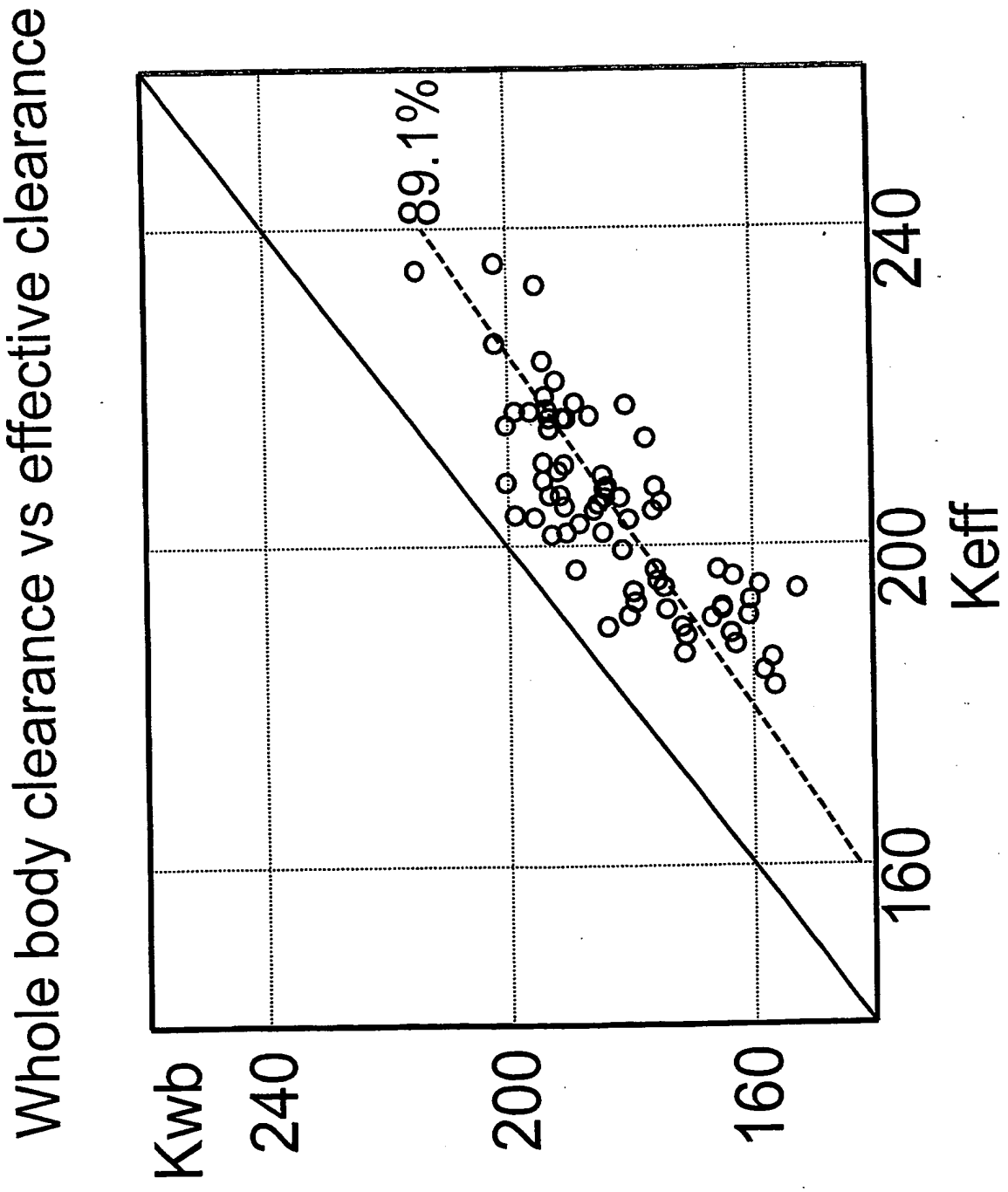
Whole body clearance vs effective clearance
89.1%
Kwb
240
200
160
240
200
160
Keff

Fig. 20

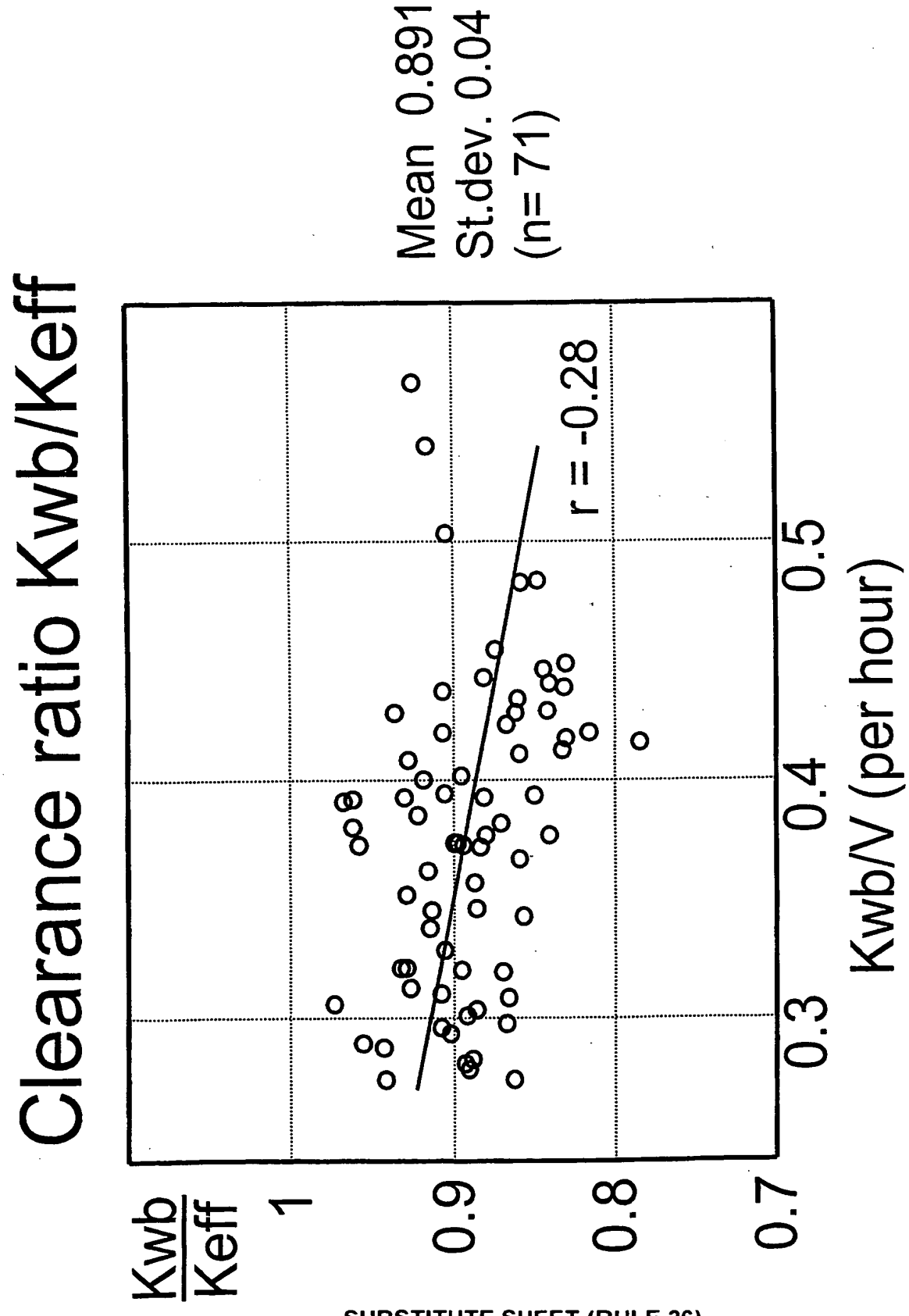
Clearance ratio Kwb/Keff
Mean 0.891
St.dev. 0.04
(n= 71)
r = -0.28
Kwb/Keff
1
0.9
0.8
0.7
0.3
0.4
0.5
Kwb/V (per hour)

Fig. 21

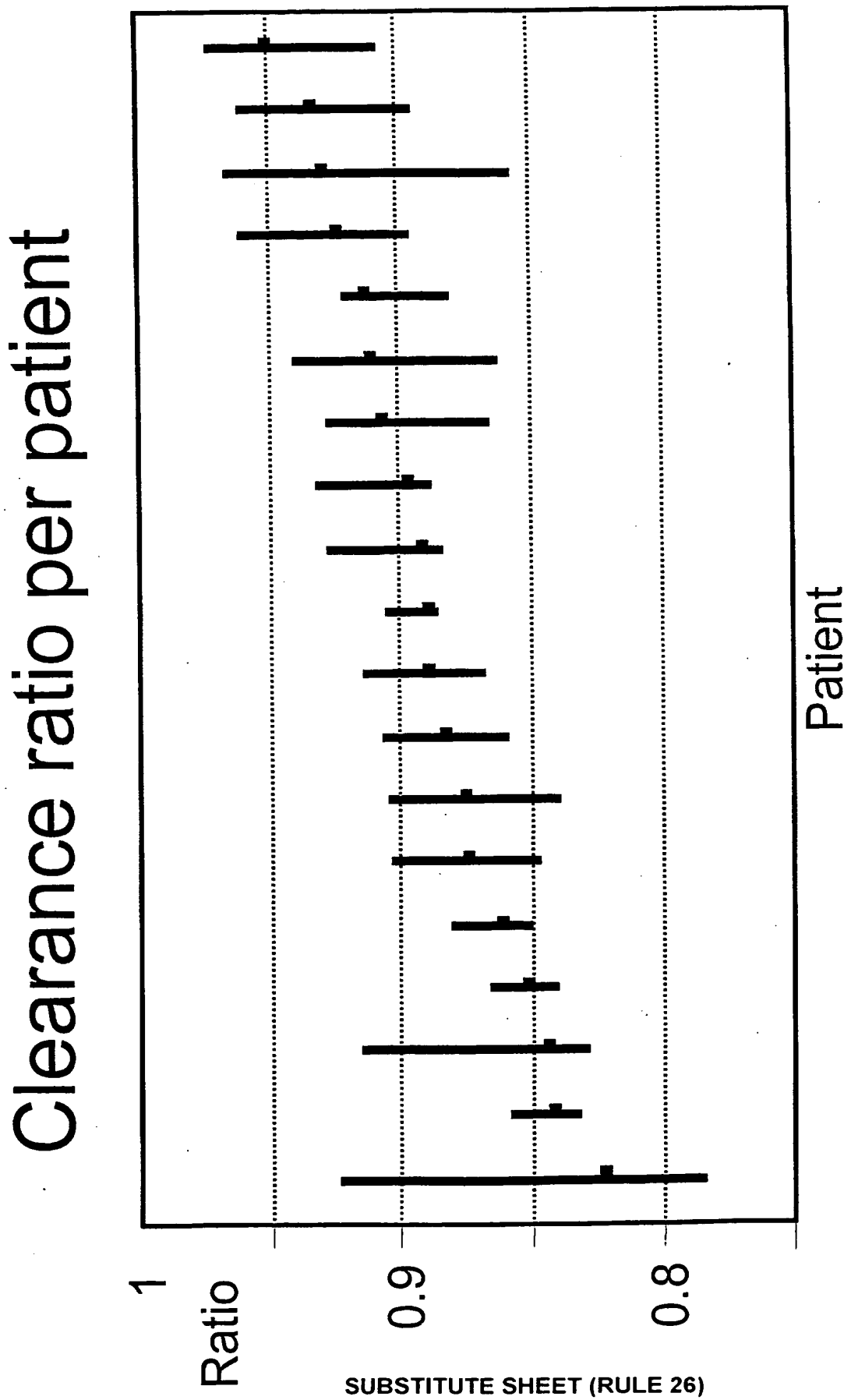

Fig. 22

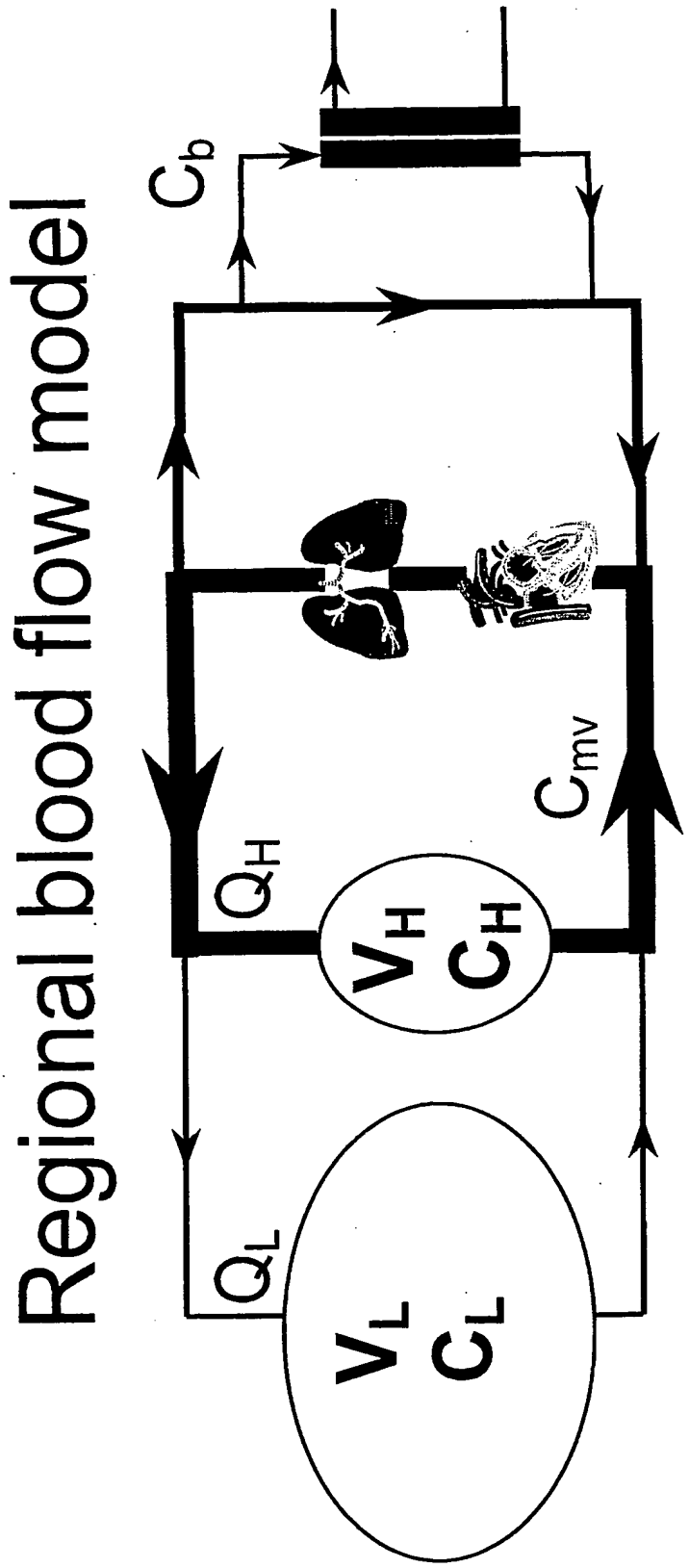
Regional blood flow model
C_b
Q_H
V_H C_H
C_{mv}
Q_L
V_L C_L
$C_{mv} = \frac{Q_H \cdot C_H + Q_L \cdot C_L}{Q_H + Q_L}$
$C_{eq} = \frac{V_H \cdot C_H + V_L \cdot C_L}{V_H + V_L}$
$C_L > C_{eq} > C_{mv} > C_H > C_b$

Fig. 23

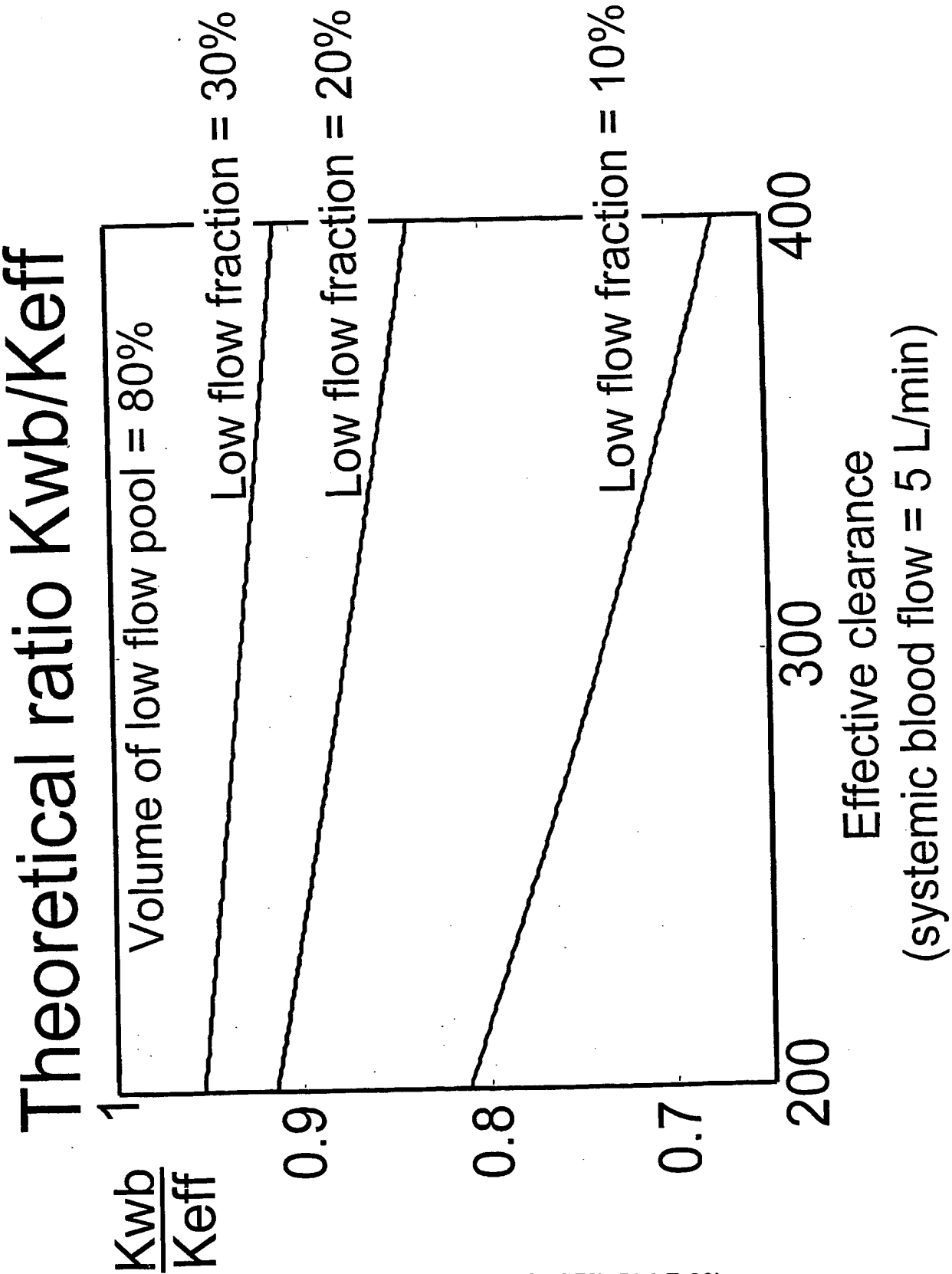
Theoretical ratio Kwb/Keff
Kwb/Keff
1
0.9
0.8
0.7
Volume of low flow pool = 80%
Low flow fraction = 30%
Low flow fraction = 20%
Low flow fraction = 10%
200
300
400
Effective clearance
(systemic blood flow = 5 L/min)

Fig. 24